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RESEARCH MEMORANDUM

AN ANALYSIS OF A NUCLEAR POWERED SUPERCRITICAL-WATER CYCLE FOR AIRCRAFT PROPULSION

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AN ANALYSIS OF A NUCLEAR POWERED SUPERCRITICAL-WATER CYCLE FOR AIRCRAFT PROPULSION

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SUMMARY

An analysis to indicate the feasibility of the supercritical water compressor jet cycle for nuclear powered aircraft is presented. Performance values of the cycle are given for a range of design-point engine operating conditions at supersonic flight conditions of 1.5 flight Mach number and 50,000, 40,000, and 30,000 feet altitudes, and at subsonic flight conditions of 0.9 flight Mach number and 40,000 feet altitude.

Calculations were made at these combinations of flight conditions for various steam temperatures at the reactor outlet and steam pressures at the turbine outlet (the steam pressure at the reactor outlet was fixed at 5000 lb/sq in.) to evaluate the combination of compressor pressure ratio and Mach number of the air entering the heat exchanger which result in maximum thrust per unit engine weight (or minimum airplane gross weight). Airplane gross weight, reactor heat release, air flow rate, the engine frontal area, and heat exchanger frontal area required at these conditions for maximum thrust per unit engine weight are evaluated for a range of values of lift-drag ratio of the airplane assuming a fixed value of the ratio of airplane structural to gross weight of 0.35 and a fixed value of the sum of the reactor, shield, payload, and auxiliary weights of 150,000 pounds.

The combination of compressor pressure ratio and Mach number of air entering exchanger for minimum airplane gross weight is not the same as that for minimum reactor heat release, minimum engine frontal area, or minimum exchanger frontal area. In general, when operation is at the

combination for minimum airplane gross weight, reasonable values of reactor heat release rates and exchanger frontal areas but high values of engine frontal areas are obtained.

The performance of the cycle at a pressure ratio and exchanger inlet Mach number which result in a 2 percent greater gross weight but about 18 percent lower engine frontal area than the minimum gross weight case, for a given set of flight and steam operating conditions, is presented in the following table. These values are representative of the performance of the cycle at the flight and altitude conditions listed.

Sum of reactor, shield, payload, and auxiliary weights, lb	150,000
Ratio of airplane structure to gross weight	0.35
Flight Mach number	1.5
Altitude, ft	50,000
Over-all lift to drag ratio of airplane	5
Steam temperature at reactor outlet, $^{\circ}R$	1460
Steam pressure at reactor outlet, lb/sq in.	5000
Steam pressure at turbine outlet, lb/sq in.	1250
Compressor pressure ratio	1.27
Mach number of air at exchanger inlet	0.18
Thrust per unit air flow rate, lb/(lb/sec)	12.37
Engine weight per unit air flow rate, lb/(lb/sec)	12.65
Thrust per unit engine weight, lb/lb	0.98
Air flow rate, lb/sec	5440
Steam flow rate, lb/sec	577
Reactor heat release rate, Btu/sec	460,000
Airplane gross weight, lb	336,000
Engine weight, lb	68,500
Exchanger weight, lb	39,400
Structure weight, lb	117,500
Compressor frontal area, sq ft	570
Exchanger frontal area, sq ft	1195

In order for the exchanger to fit into the duct determined by compressor frontal area, the exchanger must be slanted at an angle of approximately 30° with the horizontal axis of the duct.

The performance of this typical case indicates that the cycle is one requiring low compressor pressure ratios, and one developing low thrust per unit air flow; consequently, it requires high air flow rates and large compressor and exchanger frontal areas.

INTRODUCTION

Analyses to determine some of the characteristics of various aircraft propulsion cycles utilizing nuclear energy are being made at the

NACA Lewis laboratory. Studies of the direct-air and liquid-metal turbojet cycles are presented in references 1 and 2, the liquid-metal turbine-propeller cycle in reference 3, and the liquid-metal ducted-fan cycle in reference 4.

A supercritical water-compressor jet cycle is described in reference 5. In this cycle, water at supercritical pressure is the reactor coolant and also serves as the moderating material in the reactor. A favorable characteristic of this cycle is that relatively low coolant temperatures out of the reactor are encountered. Also, the use of water as a coolant may relieve the corrosion problem in the reactor that exists with liquid-metal coolants. The water, however, is a poorer heat-transfer material than liquid metals so that the heat-removal problem in the reactor at high heat-release rates becomes important. In addition, the high supercritical pressure at which the coolant is maintained in the reactor creates another important reactor design problem. The water is highly pressurized in order to avoid boiling during the heating process. The sudden and extreme variation in fluid properties that accompanies boiling aggravates the heat-transfer design problem and also might further complicate reactor control. In short, this cycle is characterized by some reactor development problems that are more severe and some that are less severe than those encountered in the liquid-metal and air-cooled reactor. Inasmuch as it offers some possible advantages in the development of nuclear-powered aircraft, the cycle deserves further investigation.

Many of the important performance parameters of the supercritical water-compressor jet cycle, such as airplane gross weight and reactor heat release required, are functions of the airplane characteristics as well as of the engine characteristics. A complete cycle study requires detailed studies of all factors involved in reactor, airplane, and engine design and performance, for both design and off-design-point operation.

As a first step, an exploratory design-point analysis of this cycle has been made which utilizes many simplifying assumptions to avoid some of the detailed studies just described. These assumptions are listed and discussed in appendix A. In the analysis, the performance of the cycle is evaluated over a wide range of flight and engine design-point operating conditions in order to determine some of the effects of these operating conditions on cycle performance. Both supersonic and subsonic flight conditions are studied. The supersonic case investigated was at a flight Mach number of 1.5 and altitudes of 50,000, 40,000, and 30,000 feet. The subsonic case was at a flight Mach number of 0.9 and altitude of 40,000 feet. The engine operating conditions investigated were supercritical steam temperature at the reactor outlet, steam pressure at turbine outlet (the steam pressure at turbine inlet being fixed), air compressor pressure ratio, and Mach number of the air entering the heat exchanger. The effect of over-all lift-drag ratio of the airplane was also studied.

Some of the parameters that are used to evaluate the performance of the cycle are airplane gross weight, reactor heat release rate, engine frontal area, and exchanger frontal area. In general, optimum operating conditions for any one of these parameters are not the optimum conditions for the other parameters. In this analysis at each set of given flight conditions and steam conditions, the values of compressor pressure ratio and Mach number of air entering the exchanger which result in maximum thrust per unit engine weight (or minimum airplane gross weight) were determined. In general, this combination of compressor pressure ratio and exchanger-inlet air Mach number results in reasonable values of the other performance parameters. Values of airplane gross weight, reactor heat release rate, air flow, and compressor frontal area at these conditions were evaluated for a range of lift-drag ratios of the airplane assuming a fixed value of airplane structure to gross weight ratio and a fixed value for the sum of reactor, shield, payload, and auxiliary weights. The effect of the variation in individual engine operating variables on the performance and sizes of the components is included in order to help give a clearer picture of the effect of these variables on over-all cycle performance. 2593

DESCRIPTION OF CYCLE

A schematic diagram of the cycle is shown in figure 1. High-temperature steam at supercritical pressure leaves the reactor and is expanded through a turbine, producing useful work output. It then passes through a heat exchanger where it is completely condensed. The condensate is then pumped to a sufficiently high pressure to maintain the flow of the water in the closed water circuit and enters the reactor where it is heated to operating temperature.

Air, which is the propulsive fluid, enters the inlet diffuser where it is compressed. It is further compressed in the compressor and then heated in the heat exchanger by the condensing steam. The heated air is then expanded through the exhaust nozzle from which it issues as a high-velocity jet.

The steam turbine drives both the air compressor and condensate pump. The turbine-to-pump drive is assumed to be direct, whereas the turbine drives the air compressor through reduction gears.

SYMBOLS

The following symbols are used in this report:

A_c	compressor frontal area, sq ft
A_x	exchanger frontal area, sq ft
$A_{x,f}$	exchanger air flow area, sq ft
C_v	exhaust nozzle velocity coefficient
D_f	fuselage drag, lb
D_n	nacelle drag, lb
D_t	tail drag, lb
D_{tot}	total airplane drag, lb
D_w	wing drag, lb
d	hydraulic diameter of air passage
F	net thrust, lb
f	free flow factor in heat exchanger
g	acceleration due to gravity, ft/sec^2
ΔH_c	compressor work, Btu
ΔH_p	condensate pump work, Btu
ΔH_t	turbine work, Btu
h	heat transfer coefficient, $\frac{\text{Btu}}{\text{sec-}^{\circ}\text{F-sq ft}}$
hp_t	turbine horsepower
k	thermal conductivity, $\frac{\text{Btu-ft}}{\text{sec-}^{\circ}\text{F-sq ft}}$
L	lift of airplane, lb
l	length of heat transfer passage, ft

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M_2 Mach number of air entering heat exchanger

P_A steam pressure at reactor outlet, lb/sq in.

P_B steam pressure at turbine outlet, lb/sq in.

P_C water pressure at exchanger outlet, lb/sq in.

P_D water pressure at condensate pump outlet, lb/sq in.

Pr Prandtl number

P_0 total pressure of free stream air, lb/sq ft

P_1 total pressure of air at compressor inlet, lb/sq ft

P_2 total pressure of air at compressor outlet, lb/sq ft

P_3 total pressure of air at exchanger outlet, lb/sq ft

p_0 ambient air static pressure, lb/sq ft

Q_r reactor heat release rate, Btu/sec

Q_x heat-exchanger heat flow, Btu/sec

Re Reynolds number

T_A total temperature of steam at reactor outlet, $^{\circ}R$

T_B total temperature of steam at turbine outlet, $^{\circ}R$

T_C total temperature of condensate at exchanger outlet, $^{\circ}R$

T_D total temperature of water at condensate pump outlet, $^{\circ}R$

T_b bulk total temperature of air in the exchanger, $^{\circ}R$

T_{sat} saturation temperature of steam corresponding to steam pressure, P_B, $^{\circ}R$

T_w wall temperature in exchanger, $^{\circ}R$

$T_{w,eff}$ effective wall temperature in exchanger, $^{\circ}R$

$T_{w,equ}$ equivalent constant wall temperature in exchanger, $^{\circ}R$

T_1	total temperature of air at compressor inlet, $^{\circ}R$
T_2	total temperature of air at compressor outlet, $^{\circ}R$
T_2'	total temperature of air after being heated by condensing phase of the steam, $^{\circ}R$
T_3	total temperature of air at exchanger outlet, $^{\circ}R$
V_j	jet velocity, ft/sec
V_0	airplane velocity, ft/sec
W_b	weight of gear box, lb
W_c	weight of compressor, lb
W_e	weight of engine, lb $W_e = W_b + W_c + W_{t+p} + W_x$
W_g	gross weight of airplane, lb $W_g = W_e + W_k + W_s$
W_k	weight of auxiliary group; shield, reactor, payload, and piping, lb
W_s	airplane structural weight, lb
W_{t+p}	weight of turbine and condensate pump, lb
W_x	weight of heat exchanger, lb
w_a	air flow rate, lb/sec
w_s	steam flow rate, lb/sec
η_b	reduction gearing efficiency
η_c	compressor efficiency
η_f	fin effectiveness
η_p	condensate pump efficiency
η_t	turbine efficiency

ANALYSIS

Equations for Performance Parameters

Some of the important parameters used to evaluate the characteristics of the cycle are airplane gross weight W_g, reactor heat release required Q_r, air flow w_a, compressor frontal area A_c, and exchanger frontal area A_x. The value of L/D_{tot} that can be obtained at supersonic flight in general depends on A_c.

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In reference 2 it is shown that the airplane gross weight can be expressed as

$$W_g = \frac{W_k}{1 - \frac{W_s}{W_g} - \frac{D_{tot}}{L}\frac{W_e}{F}} \tag{1a}$$

Another form of equation (1a) can be obtained by expressing the total drag as the sum of the wing drag, fuselage drag, tail drag, and nacelle drag. Thus the net thrust, which is equal to the total drag, is

$$F = D_{tot} = D_w + D_f + D_t + D_n$$

Inasmuch as the nacelle drag is often charged against the engine

$$F - D_n = D_w + D_f + D_t$$

and equation (1a) can be rewritten as

$$W_g = \frac{W_k}{1 - \frac{W_s}{W_g} - \frac{W_e}{F-D_n}\frac{D_w + D_f + D_t}{L}} \tag{1b}$$

It is apparent from equations (1a) or (1b) that for assumed values of W_k and W_s/W_g, airplane gross weight is a minimum at those conditions giving a maximum value of $\frac{L}{D_{tot}}\frac{F}{W_e}$ or its equivalent $\frac{L}{D_w + D_t + D_f}\frac{F-D_n}{W_e}$.

In the analysis, a constant L/D_{tot} was chosen, mainly to avoid the more complicated calculations involved in the evaluation of all the drag forces. For this constant L/D_{tot}, performance at maximum F/W_e was determined. For one case, constant $L/(D_w + D_t + D_f)$ was assumed, a given airplane configuration was selected, the nacelle drag of this configuration was evaluated, and the performance at maximum $\frac{F-D_n}{W_e}$ was determined.

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The net thrust per unit engine weight is the ratio of the net thrust per unit air flow rate to the engine weight per unit air flow rate

$$\frac{F}{W_e} = \frac{F/w_a}{W_e/w_a} \tag{2}$$

The reactor heat release can be expressed as $Q_r \equiv \frac{Q_r}{w_a}\frac{w_a}{F} F$ and substituting in this identity $F = W_g \frac{D_{tot}}{L}$

$$Q_r = \frac{Q_r}{w_a}\frac{w_a}{F}\frac{D_{tot}}{L} W_g \tag{3}$$

The air flow

$$w_a = \frac{F}{F/w_a} = \frac{W_g}{\frac{L}{D_{tot}}\frac{F}{w_a}} \tag{4}$$

The compressor frontal area

$$A_c = \frac{w_a}{w_a/A_c} \tag{5}$$

A value for the corrected air flow per unit compressor frontal area is assumed for this analysis (see appendix A). This value and the flight conditions determine w_a/A_c.

The exchanger frontal area

$$A_x = \frac{A_{x,f}}{f} = \frac{A_{x,f}}{w_a f} w_a \tag{6}$$

The value of $w_a/A_{x,f}$ is evaluated from the air conditions and the Mach number at the exchanger inlet, and f depends on the exchanger configuration assumed.

Equations (1a), and (2) to (6) show that for any assumed fixed values of W_k, W_s/W_g, and L/D_{tot} the performance parameters F/W_e, W_g, Q_r, A_x, and A_c at any set of design operating conditions can be determined by evaluating the values of F/w_a, W_e/w_a, and Q_r/w_a at these conditions.

Evaluation of Thrust per Unit Air Flow Rate, F/w_a

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The thrust per unit air flow rate is equal to $F/w_a = \frac{1}{g}(V_j - V_0)$ so that, for a given flight speed, evaluating F/w_a consists essentially in evaluating V_j. The jet velocity is a function of the air temperature at inlet to the exhaust nozzle T_3, and the pressure ratio across the nozzle P_3/p_0, a constant value of nozzle velocity coefficient being assumed. The values of P_3/p_0 and T_3 depend on the given set of operating conditions of both the closed steam cycle and the air cycle.

Steam cycle. - All steam conditions throughout the steam cycle and energy interchanges in the various components, such as the turbine work per unit steam flow $\Delta H_t/w_s$, the heat exchanged in the condenser per unit steam flow for subcooling to 20° F below the saturation temperature Q_x/w_s, the condensate pump work per unit steam flow $\Delta H_p/w_s$, and the reactor heat release per unit steam flow Q_r/w_s are determined using steam tables (ref. 6). The following table gives a list of the combinations of design-point steam conditions investigated at various flight and altitude conditions. The minimum value of T_A is limited to 1360° R in order to avoid excessive condensation of the steam expanding through the turbine.

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Flight Mach number	Altitude, ft	P_A, lb/sq in.	T_A, °R	P_B, lb/sq in.
1.5	50,000	5000	1660	2500
			1560	2500
			1460	2500
				1700
				1250
				833
				625
			1360	2500
1.5	40,000	5000	1460	2500
				1250
				625
1.5	30,000	5000	1460	2500
				1250
				625
0.9	40,000	5000	1660	1250
			1560	1250
			1460	2500
				1700
				1250
				833
				625
			1360	1250

The total work available to drive the air compressor, with gear losses neglected, is

$$\Delta H_c = w_s \left(\frac{\Delta H_t}{w_s} - \frac{\Delta H_p}{w_s}\right)$$

Air cycle. - Entering air is compressed in the diffuser to a pressure ratio P_1/p_0 which depends on flight conditions and diffuser efficiency. Further compression in the compressor to a given pressure ratio P_2/P_1 requires a compressor work per unit air flow $\Delta H_c/w_a$ and an accompanying T_2 which is evaluated from air tables (ref. 7).

Equating the total compressor work $\Delta H_c \equiv w_a \dfrac{\Delta H_c}{w_a}$ to the work available from the steam results in

$$\frac{w_a}{w_s} = \frac{\dfrac{\Delta H_t}{w_s} - \dfrac{\Delta H_p}{w_s}}{\dfrac{\Delta H_c}{w_a}} \tag{7}$$

This equation shows that for a given set of steam operating conditions the ratio w_a/w_s is a function of $\Delta H_c/w_a$ (or P_2/P_1).

Air entering the exchanger at T_2 and P_2 acquires all the heat released by the steam so that the heat gained per unit air flow $\frac{Q_x}{w_a} \equiv \left(\frac{Q_x}{w_s}\right)\left(\frac{w_s}{w_a}\right)$. The air temperature at exchanger outlet T_3 is determined from T_2 and Q_x/w_a by air tables. The air temperature T_3 cannot exceed T_B so that any value of P_2/P_1 which results in such an ambiguous solution of the equations is not in the achievable operating range of the engine.

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The method used to calculate the pressure ratio across the exchanger P_3/P_2 is described in a subsequent discussion on heat exchanger performance. The jet velocity is evaluated from P_3/p_0 and T_3 where $\frac{P_3}{p_0} = \frac{P_3}{P_2}\frac{P_2}{P_1}\frac{P_1}{p_0}$.

Heat-Exchanger Calculations

An exchanger configuration as shown in figure 2 was selected in order to provide a basis for evaluating the exchanger weight, size, and pressure drop (for further discussion of exchanger configuration, see appendix A). The heat-exchanger calculations are based on the assumption that the finned passage through which the air flows is a tube having an equivalent diameter, in this case, of 0.01113 feet.

For the more general case where the steam from the turbine discharge is superheated, the cooling of the steam is divided into two stages for the purpose of calculation. The superheated steam is first considered to be cooled to dry saturated steam in the first stage and is then completely condensed and subcooled in the second stage. The exchanger calculations are based on the assumption that the heat exchanger is equivalent to two exchangers in series; in the first exchanger the air is heated from T_2 to an intermediate temperature T_2' by the condensing steam, and in the second exchanger the air is further heated to the temperature T_3 by the superheated steam. Figure 3 shows this orientation of exchangers as well as the temperatures of the air and steam. The sum of the length-diameter ratio l/d of each of these two exchangers is the l/d of the equivalent single exchanger, and the sum of the pressure drops in the two exchangers is the over-all pressure drop of the equivalent single exchanger.

Evaluation of l/d. - Heat-transfer coefficients of the air are evaluated with the equation given in reference 8.

$$\frac{hd}{k} = 0.023\ Re^{0.8} \left(\frac{T_b}{T_w}\right)^{0.8} Pr^{0.4}$$

where T_b is the bulk temperature of the air and T_w is the wall temperature (which in this case is assumed equal to the steam temperature). The Reynolds number Re is evaluated from the velocity and density based on bulk temperature of air, while all the other properties are evaluated at the wall temperature.

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For the first exchanger (in which air is heated by condensing steam) an average value of h is determined at an air bulk temperature of $\frac{1}{2}(T_2 + T_2')$ and the corresponding wall temperature (saturated steam temperature). This value of h is used to evaluate the fin effectiveness and the effective wall temperature at the inlet and outlet of the exchanger (see sample calculations in appendix B). For the second exchanger, an average value of h is evaluated at an air bulk temperature of $\frac{1}{2}(T_2' + T_3)$ and its corresponding average wall temperature of $\frac{1}{2}(T_{sat} + T_B)$. For each exchanger the log mean temperature difference is evaluated from the temperature differences between the effective wall temperature and the air bulk temperature at both inlet and outlet of each exchanger. The l/d of each exchanger is evaluated from the equation

$$l/d = \frac{Q_x/w_a}{4\ h\left(\frac{A_{x,f}}{w_a}\right)(\text{log mean temperature difference})}$$

Q_x/w_a is evaluated from Q_x/w_s which is fixed for a given set of steam cycle conditions, and w_a/w_s which is determined as previously described. The value of $w_a/A_{x,f}$ is evaluated from the values of P_2 and T_2 of air and the given value of the Mach number at the inlet to the exchanger.

Evaluation of air pressure drop. - In each exchanger a constant equivalent wall temperature is evaluated which results in the same log mean temperature difference as previously obtained to calculate l/d from effective wall temperatures. The air pressure drops are determined from these constant equivalent wall temperatures and the pressure-drop charts of reference 2, which are based on the method presented in reference 9. The pressure ratio across each exchanger is evaluated from the values of the constant equivalent wall temperature, the bulk air temperatures entering and leaving each exchanger and the Mach number of the air entering each exchanger. The Mach number of the air entering the second exchanger is equal to that of the air leaving the first exchanger, which is evaluated from the air flow rate per unit area and exit conditions from the first exchanger.

In order to account for additional losses in pressure due to the turning of the air flow into and out of the exchanger, the pressure drop previously evaluated is increased by 15 percent. Referring to the sample calculations presented in appendix B will help clarify the heat-exchanger calculations.

Evaluation of Engine Weight per Unit Air Flow Rate W_e/w_a

The engine weight consists of the weights of exchanger, compressor, reduction gears, steam turbine and condensate pump. In appendix A, equations used to evaluate the weights of these components are given.

Evaluation of Reactor Heat Release per Unit Air Flow Rate Q_r/w_a

The reactor heat release Q_r/w_a is obtained from the values of Q_r/w_s and w_a/w_s. The value of Q_r/w_s is fixed for a given set of steam cycle conditions, and the value of w_a/w_s obtained from equation (7).

A sample set of calculations illustrating the method used in evaluating cycle performance is given in appendix B.

RESULTS AND DISCUSSION

In the analysis the performance at two flight Mach numbers was investigated: a supersonic case at a flight Mach number of 1.5 and altitudes of 50,000, 40,000, and 30,000 feet; and a subsonic case at a flight Mach number of 0.9 and altitude of 40,000 feet.

Supersonic Flight Conditions

Effect of compressor pressure ratio P_2/P_1 and M_2. - In order to show the effect of P_2/P_1 and M_2 the following fixed set of flight and engine operating conditions were arbitrarily selected: altitude, 50,000 feet; reactor outlet steam temperature T_A, 1460° R; reactor outlet steam pressure P_A, 5000 pounds per square inch; and turbine outlet steam pressure P_B, 1250 pounds per square inch.

Figure 4 shows the effect of varying P_2/P_1 and M_2 on several performance parameters. Figure 4(a) shows the variation in thrust per unit engine weight F/W_e and thrust per unit air flow rate F/w_a. It is apparent that there are values of both P_2/P_1 and M_2 which result in maximum F/W_e (that is, minimum gross weight) for the set of fixed design conditions. In figure 4(a) a maximum value of F/W_e of 1.02 is obtained at a value of P_2/P_1 equal to 1.214 and a value of M_2 equal to 0.20. The corresponding value of F/w_a is 10.0 pounds thrust per pound per second. Figure 4(b) presents the corresponding values of reactor heat release rate Q_r air flow rate w_a, and exchanger frontal area A_x required, for values of L/D_{tot} equal to 5, W_k equal to 150,000 pounds, and W_s/W_g equal to 0.35. There are also optimum values of P_2/P_1 and M_2 resulting in minimum Q_r, in minimum w_a (or minimum A_c), and in minimum A_x (these being functions of the values of L/D_{tot}, W_s/W_g, and W_k as well as steam conditions T_A, P_A, and P_B). From figure 4(b) the minimum Q_r of 434×10^3 Btu per second is obtained at a value of M_2 of 0.15 and a value of P_2/P_1 of 1.230. This Q_r is about 4 percent lower than the Q_r at conditions for maximum F/W_e. Minimum w_a of 4800 pounds per second occurs at about a P_2/P_1 of 1.34 and M_2 of about 0.12. This w_a is about 35 percent lower than the w_a at conditions for maximum F/W_e. Minimum exchanger frontal area A_x of 1100 square feet is obtained at a P_2/P_1 of about 1.30 and M_2 of 0.20 which is approximately 20 percent lower than the A_x at conditions for maximum F/W_e.

Figures 5 and 6 show how the performance of the various components of the engine are interrelated and affected by variation in compressor pressure ratio and M_2. These help give a clearer picture of cycle performance variation with design-point operating variables. Figure 5 illustrates the effect produced by varying P_2/P_1 while other cycle conditions are held constant (T_A, 1460° R; P_A, 5000 lb/sq in.; P_B, 1250 lb/sq in.; M_2, 0.20). Figure 5(a) shows the variation in air temperature leaving the exchanger T_3, exchanger l/d, pressure ratio across the exchanger P_3/P_2, available pressure ratio across the exhaust nozzle P_3/p_0, and F/w_a, as P_2/P_1 varies. As a result of equating the net work output of the steam cycle to the compressor work input, and in the exchanger equating the heat released by the steam to the heat absorbed by the air, T_3 increases as P_2/P_1 is increased. This increase in T_3 necessitates increases in the l/d of the exchanger, which becomes large as T_3 approaches the maximum steam temperature into the exchanger T_B (which is fixed). The pressure drop in the exchanger increases with l/d; hence the drop in P_3/P_2 as P_2/P_1 increases. The nozzle pressure ratio $\frac{P_3}{p_0} = \frac{P_1}{p_0}\frac{P_2}{P_1}\frac{P_3}{P_2}$, where $\frac{P_1}{p_0}$ is fixed. At first as P_2/P_1 increases, the accompanying drop in P_3/P_2 is small enough so that P_3/p_0 increases. This increase in P_3/p_0 together with an increase in T_3 results in a large increase in F/w_a. Soon a value of P_2/P_1 is reached where the drop in P_3/P_2 is large enough to result in a decrease in P_3/p_0, and eventually P_3/p_0 is decreasing rapidly enough to cause F/w_a to start leveling off despite the increasing T_3.

Figure 5(b) shows the effects of P_2/P_1 on the weights per unit air flow of engine components and the over-all engine. The values of compressor weight W_c, gearing weight W_b, turbine and pump weight W_{t+p} are relatively small and their variation depends largely on the weight assumptions made. The weight of the exchanger W_x is the major item influencing engine weight W_e. The exchanger weight increases almost directly with l/d; hence, the values of W_x/w_a and W_e/w_a increase with P_2/P_1, this increase becoming large when the increase in l/d becomes very rapid.

The variation in F/W_e (also shown in fig. 5(b)) depends on the manner in which F/w_a and W_e/w_a vary. It is apparent that if F/W_e is at first increasing with increasing P_2/P_1, it will eventually reach a maximum and then decrease because F/w_a will eventually be leveling off whereas W_e/w_a will be continuously increasing.

Figure 5(c) presents the variation in airplane gross weight, reactor heat release, total thrust required, engine weight, air and steam

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flow rates and the compressor and exchanger frontal areas with compressor pressure ratio. The values of these parameters are based on fixing the values of L/D_{tot} equal to 5, W_k equal to 150,000 pounds, and W_s/W_g equal to 0.35. It is to be noted from figure 5(c) that minimum gross weight, engine weight, and thrust required all occur when F/W_e is a maximum, and that minimum reactor heat release is required when the steam flow rate w_s is a minimum. Minimum compressor frontal area which depends directly on air flow occurs at minimum air flow.

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The effect of varying M_2 on heat-exchanger performance largely determines its effect on over-all cycle performance. In figure 6, a range of values of M_2 is studied, the value of P_2/P_1 being fixed at 1.21. Other fixed operating conditions are the same as for figure 5. For this case, fixing steam cycle conditions and P_2/P_1 fixes T_3. Increased M_2 increases the heat-transfer coefficient and also the air flow through any exchanger flow passage, with an over-all effect that l/d necessary to obtain a given T_3 is very nearly proportional to $M_2^{0.2}$. Thus, l/d increases slightly with M_2. Increased M_2 increases the air flow per unit flow area of the exchanger $w_a/A_{x,f}$, which is mostly influential in decreasing W_x/w_a and A_x/A_c. On the other hand, the pressure drop through the exchanger increases with increased M_2 resulting in a continual drop in F/w_a. At some value of M_2, the decrease in F/w_a eventually overcomes the effect of decrease in W_e/w_a, so that F/W_e reaches a maximum value and then drops off.

In the analysis, performance at maximum F/W_e was considered most interesting so that P_2/P_1 and M_2 were selected for maximum F/W_e. The engine performance at conditions for maximum F/W_e usually results in reasonable values of Q_r, A_c, and A_x, as will be shown subsequently.

Effect of steam pressure at turbine outlet P_B. - Maximum values of F/W_e and the corresponding values of P_2/P_1, M_2, and F/w_a such as those discussed for figure 4 (which was for a turbine discharge pressure P_B of 1250 lb/sq in.) are plotted for a range of values of P_B in figure 7. The maximum value of P_B was limited to 2500 pounds per square inch. It is noted from figure 7 that for the given conditions F/W_e increases with increased P_B, the values ranging from about 0.90 at a P_B equal to 625 pounds per square inch to about 1.18 at a P_B equal to 2500 pounds per square inch. The corresponding values of F/w_a show the same trend, increasing from 8.7 to 11.5 pounds per pound per second as P_B varies from 625 to 2500 pounds per square inch. Other items of interest seen from the figure are that M_2 varies only slightly with P_B, its value being close to 0.20 while P_2/P_1 decreases as P_B increases. The values of P_2/P_1 range from 1.23 to 1.16, which values are readily attainable in the single-stage compressor assumed.

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Figure 8 is included to indicate the influence of P_B on component performance in order to show more clearly its effect on over-all performance. Several curves of figure 5 (P_B = 1250 lb/sq in.) were cross-plotted against T_3 and similar sets of curves plotted for values of P_B of 625 and 2500 pounds per square inch. Other fixed operating conditions are T_A, 1460° R; P_A, 5000 pounds per square inch; and M_2, 0.20. Increasing P_B increases the steam temperatures in the exchanger resulting in lower l/d required to obtain a given T_3 (with consequent lower pressure drop of the air in the exchanger). On the other hand, at higher P_B, less turbine work per unit steam flow is obtained which results in lower P_2/P_1. The net effect of increased P_B on F/W_e depends on whether the benefits of lower pressure drop in the exchanger and lower exchanger weight overbalance the effect of lower P_2/P_1. From figure 8 it is apparent that for the given set of conditions, this is the case and higher P_B improves F/W_e.

The over-all performance of the cycle operating at values of P_2/P_1 and M_2 giving maximum F/W_e (that is minimum W_g) for a range of values of L/D_{tot} is presented in figure 9. Values of W_g are plotted against values of Q_r for values of L/D_{tot} equal to 4, 5, and 6 in figure 9(a). Lines of constant P_B are also located on these plots. As for most of the previous figures, the given conditions are T_A, 1460° R; P_A, 5000 pounds per square inch; W_k, 150,000 pounds; and W_s/W_g, 0.35.

It is seen from the figure that values of W_g ranging from 300,000 to 400,000 pounds and values of Q_r ranging from 350,000 to 650,000 Btu per second (depending on the value of L/D_{tot} assumed) are obtained for this set of conditions. It should be remembered that both W_g and Q_r vary directly with W_k. Therefore, for any value of W_k other than 150,000 pounds, values of W_g and Q_r are obtained by multiplying the values of figure 9(a) by the factor $W_k/150,000$.

Values of w_a, A_c, and A_x/A_c corresponding to the values of figure 9(a) are presented in figure 9(b). The very high values of w_a (420 to 1150 lb/sec) required are mainly due to low values of F/w_a characteristic of the cycle and the low values of L/D_{tot} encountered at the flight conditions (flight Mach number, 1.5; altitude, 50,000 ft) of figure 9. At these flight conditions the compressor handles only 9.53 pounds of air per second per square foot of frontal area with consequent huge engine frontal areas (450 to 1220 sq ft) required. It is interesting to note that the exchanger frontal area is about 2.0 times as large as the compressor frontal area. This requires slanting the exchanger so it will fit in any nacelle determined by compressor frontal area. The angle of slant will be about 30° with the horizontal, which is large enough so that no excessive pressure losses are incurred in deflecting the air stream into and out of the exchanger.

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Figure 10 is included to compare the performances when operating at conditions for minimum W_g (i.e. maximum F/W_e), minimum Q_r, minimum A_c, or minimum A_x. Values of W_g, Q_r, A_c, and A_x as well as the optimum values of P_2/P_1 and M_2 are plotted for a range of values of P_B. The steam temperature T_A is 1460° R and the value of L/D_{tot} assumed is 5. It is seen that higher values of P_2/P_1 are required for minimum A_c and A_x than for minimum Q_r and W_g, and that higher values of M_2 are required for minimum W_g and A_x than for minimum Q_r and A_c. It is also seen from the figure that operation at conditions for minimum W_g results in reasonable values of Q_r and A_x but somewhat high values of A_c.

Variations in P_2/P_1 and M_2 from the values giving minimum gross weight will increase W_g and Q_r only slightly but can result in appreciable decreases in A_x and A_c, hence resulting in a more reasonable airplane configuration. The performance of a case where P_2/P_1 and M_2 were chosen to give a such a combination of values of performance parameters is compared in the following table with the performance at minimum W_g. Steam operating conditions are the same for both cases and are representative of what may be attained. The performance values presented in the table are typical of what can be expected from the cycle at a flight Mach number of 1.5 and altitude of 50,000 feet.

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Fixed Conditions

Flight Mach number	1.5
Altitude, ft	50,000
L/D_{tot}	5
T_A, $^{\circ}R$	1460
P_A, lb/sq in.	5000
P_B, lb/sq in.	1250
W_k, lb	150,000
W_s/W_g	0.35

P_2/P_1	M_2	F/w_a lb/(lb/sec)	W_e/w_a lb/(lb/sec)	F/W_e lb/lb	W_g lb	w_a lb/sec	W_e lb	W_x lb	W_s lb	A_c sq ft	A_x sq ft	Q_r Btu/sec	w_s lb/sec
[a]1.27	[a]0.18	12.37	12.65	0.978	336,000	5440	68,500	39,400	117,500	570	1195	460,000	577
[b]1.21	[b].20	9.97	9.75	1.02	330,000	6620	64,500	32,500	115,500	695	1360	452,000	567

[a]Conditions for good combination of performance values.
[b]Conditions for minimum W_g.

The table shows that varying conditions slightly from the values giving minimum W_g may give somewhat more desirable performance. For the comparison shown in the table, increasing P_2/P_1 from 1.21 (the value for minimum W_g) to 1.27 and decreasing M_2 from 0.20 (the value for minimum W_g) to 0.18 result in a decrease in w_a and A_c of about 18 percent, and a decrease in A_x of about 12 percent. Only a slight increase of 2 percent in W_g and Q_r is incurred.

Effect of steam temperature at reactor outlet T_A. - So far all performance has been discussed for a T_A of 1460° R. It is interesting to see what improvement in cycle performance can be obtained by going to higher values of T_A, and also what penalty is incurred by going to lower values of T_A. In figures 11 to 13 are presented the performance of the cycle for a range of T_A from 1360° to 1660° R.

Maximum values of F/W_e and corresponding values of P_2/P_1, M_2, and F/w_a are plotted in figure 11 for a range of values of T_A, with P_B fixed at 2500 pounds per square inch (the pressure at which highest F/W_e was obtained). The optimum values of P_2/P_1 increase as T_A increases, whereas the value of M_2 remains essentially constant between 0.19 and 0.20. As expected, increasing T_A increases F/W_e and F/w_a. Increasing T_A from 1460° to 1660° R results in increased F/W_e from 1.18 to 1.33 pounds per pound and increased F/w_a from 11.5 to 13.4 pounds per pound per second. Decreasing T_A from 1460° to 1360° R results in a decreased F/W_e of 1.07 pounds per pound and a decreased F/w_a of 10.2 pounds per pound per second.

Figure 12 is included to show again what effects a design-point variable (T_A) has on component performance. At a given P_B equal to 2500 pounds per square inch and M_2 equal to 0.20, values of P_2/P_1, l/d, P_3/p_0, F/w_a, W_x/w_a, W_e/w_a, and F/W_e are plotted against T_3 for values of T_A equal to 1360°, 1460°, and 1660° R. It is seen from this figure that the main effect of increasing T_A is to increase the work output per unit steam flow which results in higher P_2/P_1. This results in greater F/w_a. Lower values of l/d are required to obtain a given T_3; this improves W_x/w_a and W_e/w_a somewhat. Both effects of increased F/w_a and decreased W_e/w_a result in higher values of F/W_e.

Figure 13(a) presents the parameters W_g against Q_r for this range of values of T_A, at values of L/D_{tot} equal to 4, 5, and 6. The P_B was fixed at 2500 pounds per square inch. The effects of T_A on W_g and Q_r are largely dependent on the value of L/D_{tot}, the effects being more pronounced the lower the value of L/D_{tot}. At an L/D_{tot} of 4, increasing T_A from 1460° to 1660° R resulted in a decrease in W_g of about 5 percent, and a decrease in Q_r of about 6 percent. Lowering T_A to 1360° from 1460° R increased W_g about 5 percent and increased Q_r almost 11 percent.

The air flows corresponding to the conditions of figure 13(a) are shown in figure 13(b). At an L/D_{tot} of 4, increasing the temperature T_A from 1460° to 1660° R results in a reduction of about 20 percent in the air flow, whereas about a 20 percent increase in air flow results when T_A is reduced from 1460° to 1360° R. The values of A_c corresponding to these air flows and the values of A_x/A_c required are also presented in figure 13(b).

Effect of altitude. - Figures 14 and 15 show the effect of altitude on the performance of the cycle. Altitudes considered were 50,000, 40,000, and 30,000 feet. The flight Mach number was held constant at 1.5, T_A at 1460° R, and P_A at 5000 pounds per square inch. Figure 14 shows the variation in F/w_a, W_e/w_a, and F/W_e (P_2/P_1 and M_2 being chosen for best F/W_e) with altitude for a given value of P_B equal to 2500 pounds per square inch. It is seen that W_e/w_a decreases rapidly as altitude decreases. This is due mainly to the increased density at lower altitude; the result is that a smaller engine is required to handle a given air flow. On the other hand, F/w_a drops off slightly as altitude decreases. The values of F/W_e increase appreciably as altitude decreases, indicating that the decrease in W_e/w_a is much more effective than the decrease in F/w_a.

In figure 15(a) the values of W_g are plotted against Q_r at the altitudes of 50,000, 40,000, and 30,000 feet. The values of W_g and Q_r are based on a fixed value of L/D_{tot} equal to 5 and values of W_s/W_g of 0.35 and W_k of 150,000 pounds. Lines of constant P_B of 2500, 1250, and 625 pounds per square inch are located on these plots. From this figure it is seen that W_g decreases as altitude decreases (because F/W_e increases), whereas Q_r reaches a minimum value at some altitude between 30,000 and 40,000 feet.

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The air flows corresponding to figure 15(a) are shown in figure 15(b). It is seen that a minimum air flow occurs at some altitude around 40,000 feet. Also shown on this figure are values of A_c, A_x/A_c, and A_x required at the various altitudes. At lower altitudes, the large increase in air handling capacity per square foot of compressor frontal area due to increased air density greatly reduces the compressor area required. For the given conditions, for example, although the required air flow at 50,000 feet and 30,000 feet altitude are about the same, the compressor frontal area required at 50,000 feet is about 2.5 times as great as that required at 30,000 feet.

Performance with nacelle drag included (for case of $L/D_w + D_t$ constant. - A set of calculations was made to evaluate the cycle performance for a range of constant values of lift-drag ratio of the wing and tail. In these calculations a constant nacelle configuration as described in appendix C was assumed and nacelle drag evaluated. For the configuration and supersonic flight conditions, a value of D_n/w_a of 2.69 pounds per pound per second is evaluated. To simplify calculations, the fuselage drag D_f is neglected (that is, assuming that the airplane consists of wing, tail, and nacelles) and equation (4b) is used to evaluate gross weights. From this equation it is apparent that maximum $(F - D_n)/W_e$ results in minimum W_g, and in the calculations P_2/P_1 and M_2 were selected to give maximum $(F - D_n)/W_e$. These values of P_2/P_1 and M_2 as well as the corresponding values of $(F - D_n)/W_e$ and F/w_a are shown plotted against P_B in figure 16. Other operating conditions held constant are T_A equal to 1460° R and P_A, 5000 pounds per square inch. Comparison with figure 7 shows that somewhat higher values of P_2/P_1 and lower values of M_2 are required where nacelle drag is considered. These conditions tend to increase F/w_a, which is evident from a comparison of the F/w_a values of figures 16 and 7.

Figure 17(a) shows the values of W_g plotted against Q_r for a range of values of $L/(D_w + D_t)$. Lines of constant P_B are located on these plots. Figure 17(b) shows the values of air flow rate and the values of L/D_{tot} that correspond to the values of figure 17(a). The expression for L/D_{tot} in terms of $L/(D_w + D_t)$ and nacelle drag is derived in appendix C.

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SUBSONIC FLIGHT CONDITIONS

A set of performance figures is also presented for the case of subsonic design-point flight conditions (flight Mach number, 0.9; altitude, 40,000 ft). For this case, higher values of L/D_{tot} are obtainable which improve airplane performance considerably.

Performance at various values of P_B. - Figure 18, similar to figure 7, presents the best value of F/W_e and corresponding P_2/P_1, M_2, and F/w_a for various values of P_B. The fixed conditions besides flight Mach number and altitude are T_A, 1460° R and P_A, 5000 pounds per square inch. For this subsonic case, it is seen that F/W_e reaches a maximum value at a P_B within the range investigated. For the given conditions, this value of P_B is about 1250 pounds per square inch. In general, the values of F/W_e, F/w_a, M_2, and P_2/P_1 are close to those obtained for the supersonic case. Briefly, as P_B ranged from 625 to 2500 pounds per square inch, values of F/W_e ranged from 1.18 to 1.13 pounds per pound, F/w_a varied from 12.7 to 13.5 pounds per pound per second, M_2 varied from 0.18 to 0.20, and P_2/P_1 ranged from 1.25 to 1.38. As previously described for the supersonic case, increasing P_B results in operating at lowered P_2/P_1 but also lower values of exchanger pressure drop and exchanger weight. The resulting effect of increased P_B on F/W_e depends on whether benefits of lower exchanger pressure drop and weight can overbalance the lower P_2/P_1. For the subsonic case, mainly because of lower ram pressure ratio, the best combination of these effects occurs at a P_B of about 1250 pounds per square inch, which is lower than the best P_B for the supersonic case.

The gross weight and heat release rate required for operation at values of T_A equal to 1460° R and P_A equal to 5000 pounds per square inch are shown in figure 19(a), for values of L/D_{tot} of 12, 15, and 18. Values of constant P_B are also located on this plot. The higher values of L/D_{tot} obtainable at subsonic flight substantially reduce the values of W_g and Q_r from those at supersonic flight. For the range of L/D_{tot} considered, W_g of about 250,000 to 260,000 pounds and values of Q_r from 80,000 to 170,000 Btu per second are obtained. The variation in W_g is much less sensitive to variation in L/D_{tot} and F/W_e at these higher values of L/D_{tot}. This can be seen from a consideration of equation (4a). The required w_a corresponding to the values of figure 19(a) are shown in figure 19(b). These values are largely dependent on the value of L/D_{tot} and for the given set of conditions range from about 1000 pounds per second at L/D_{tot} of 18 to about 1700 pounds per second at an L/D_{tot} of 12. For the subsonic design-point flight conditions considered, the w_a/A_c is 8.06 pounds per second per square foot. The values of required A_c are also shown in figure 19(b). These range from about 125 square feet to about 210 square feet. Also included on this figure are the values of A_x/A_c, which vary from about 1.8 to 2.2; this again necessitates an angle of slant of the exchanger of about 30° with the horizontal.

Performance at various values of T_A. - The effect of T_A on performance is shown in figure 20. Values of W_g are plotted against Q_r in figure 20(a) at values of L/D_{tot} of 12, 15, and 18 over a range of values of T_A from 1360° to 1660° R. The value of P_A is fixed at 5000 pounds per square inch, P_B is 1250 pounds per square inch, and again values of W_k equal to 150,000 pounds and W_s/W_g equal to 0.35 were assumed. The changes in W_g and Q_r due to varying T_A from 1360° to 1660° R are rather moderate. The largest variations which occur at an L/D_{tot} of 12 is about 3 percent for W_g and about 20 percent for Q_r. The corresponding values of F/W_e, w_a, A_c, and A_x/A_c are presented in figure 20(b).

Effect of W_s/W_g

Throughout the analysis a value of W_s/W_g equal to 0.35 was assumed. From equation (4a) the expression for the ratio of W_g at any value of W_s/W_g to W_g at W_s/W_g equal to 0.35 can readily be derived. The same expression holds for the ratio of Q_r at any value of W_s/W_g to Q_r at a value of W_s/W_g of 0.35. In figure 21 the values of these ratios of airplane gross weights or reactor heat release rates are plotted against values of W_s/W_g for a range of values of $(L/D_{tot})(F/W_e)$. These curves serve mainly to show the magnitude of the effect of W_s/W_g on W_g and Q_r. The effect is more pronounced at lower values of $(L/D_{tot})(F/W_e)$ as is expected from equation (4a).

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SUMMARY OF RESULTS

Performance values of the supercritical-water-compressor jet cycle determined from a preliminary cycle analysis for a range of flight and engine design-point operating conditions are listed in the following table. The performance values presented are at values of compressor pressure ratio and Mach number of air entering the heat exchanger which result in best thrust per unit engine weight (or minimum gross weight). Also included in the table is one case where the compressor pressure ratio and exchanger inlet Mach number were chosen to give a good compromise in the values of gross weight, reactor heat release rate, compressor frontal area, and exchanger frontal area. In the table, the sum of the reactor, shield, and auxiliary weights is taken as 150,000 pounds, structure to gross weight ratio is 0.35, and steam pressure at the reactor outlet is 5000 pounds per square inch.

Flight Mach number	Altitude, ft	T_A, °R	P_B, lb/sq in.	L/D_{tot}	W_g, lb	W_e, lb	Q_r, Btu/sec	w_a, lb/sec	A_c, sq ft	A_x/A_c	F/w_a, lb/(lb/sec)	F/W_e, lb/lb	P_2/P_1	M_2
1.5	50,000	1460	2500	4	342×10^3	72.3×10^3	646×10^3	7410	778	2.09	11.55	1.180	1.16	0.195
				5	312	52.8	471	5410	567	2.09	11.55	1.180	1.16	.195
				6	295	41.7	371	4250	447	2.09	11.55	1.180	1.16	.195
			1250	5	330	64.5	452	6620	695	1.96	9.97	1.020	1.21	.200
			625	5	353	79.5	460	8120	852	1.94	8.69	.890	1.23	.200
		1660	2500	5	300	45.0	448	4450	467	1.97	13.48	1.337	1.21	.200
		1360	2500	5	324	60.6	514	6460	677	2.14	10.04	1.069	1.13	.195
	40,000	1460	2500	5	287	36.6	431	4950	322	2.18	11.60	1.565	1.16	.185
	30,000	1460	2500	5	277	30.0	433	5380	223	2.33	10.30	1.845	1.14	.175
0.9	40,000	1460	1250	12	260	19.0	137	1610	199	1.98	13.50	1.130	1.35	0.180
				15	254	15.1	107	1250	156	1.98	13.50	1.130	1.35	.180
				18	250	12.5	88	1030	127	1.98	13.50	1.130	1.35	.180
			625	15	255	15.8	95	1340	166	1.81	12.70	1.105	1.38	.195
			2500	15	255	15.8	136	1300	161	2.18	13.12	1.085	1.25	.175
		1660	1250	15	251	13.1	99	1080	134	1.84	15.45	1.305	1.43	.185
		1360	1250	15	257	17..1	116	1500	186	2.09	11.40	1.005	1.27	.180
[a]1.5	50,000	1460	1250	5	336	68.5	460	5440	571	2.09	12.37	0.978	1.27	.180

[a]Compressor pressure ratio and M_2 chosen to give good combination of W_g, Q_r, A_c, A_x.

Only a range of values of operating conditions sufficient to show the important effects of these operating conditions and to illustrate some of the performance characteristics of the cycle, are presented in the table. Some of the cycle characteristics, seen from the table are:

1. The cycle is one having low thrust per unit air flow rate (ranging from about 8 to 16 lb/(lb/sec)) and consequently requires large air flow rates and large engine frontal areas.

2. For the range of flight and operating conditions investigated, low compressor pressure ratios (ranging from about 1.1 to 1.4) are required.

3. The cycle is one capable of operating at relatively low steam temperatures out of the reactor. Reasonably good performance is obtainable at as low a temperature as 1360° R.

Other cycle performance characteristics presented by the analysis are that

4. Lower air flows and consequently lower compressor frontal areas are obtained at higher compressor pressure ratios and lower Mach numbers of air entering the exchanger than those required for minimum airplane gross weight.

5. Lower exchanger frontal areas are obtained at higher compressor pressure ratios and about the same Mach number of air entering the exchanger as those required for minimum airplane gross weight.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 19, 1953

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APPENDIX A

ASSUMPTIONS

WEIGHTS OF ENGINE AND AIRPLANE COMPONENTS

An accurate determination of the variation in the weight of most of the airplane or engine components as a function of the design-point operating variables requires a detailed design study of each of these components. To avoid this, simplified relationships for the weights of the various airplane and engine components were used.

Compressor Weight

A characteristic of the cycle is that relatively low values of P_2/P_1 (about 1.1 to 1.4) are required for good cycle performance. In the analysis it was assumed that these values of P_2/P_1 could be obtained with a single-stage axial-flow compressor and that the weight of the compressor stage was independent of the value of P_2/P_1 but varies directly with A_c. Reference 2 presents an expression for the weight of a multistage axial-flow compressor having a pressure ratio of 1.2 per stage. From this expression, the following equation was obtained for the weight of a single stage

$$W_c/w_a = 84.8\sqrt{T_1}/P_1 \tag{8}$$

The frontal area of the compressor is determined by assuming that at static sea-level conditions the air flow per unit compressor frontal area is 25 (lb/sec)/sq ft.

Heat-Exchanger Weight

In the analysis a representative heat-exchanger design was assumed in order to provide a basis for the accurate evaluation of exchanger weight, size, and pressure drops. A schematic sketch of the heat exchanger considered is shown in figure 2. High-pressure steam from the turbine discharge flows through narrow rectangular passages 0.25 inch wide with walls of 0.02-inch steel (this wall thickness is assumed constant for all values of steam pressure entering the exchanger). These passages are separated by finning surfaces of 0.01-inch aluminum spaced 12 to the inch, the air flowing between these fins. The air-passage fin width was chosen as 0.75 inch. Calculations were made which indicated that this value gives close to the best combination of exchanger weight and pressure drop of the air flowing through the exchanger. This exchanger configuration (with rectangular steam passages) was used in order to facilitate heat-transfer and pressure-drop calculations (although tubular steam passages are probably more practical). The expression for exchanger weight using these sizes and making allowance for headers is

$$W_x/w_a = (0.595\ l/d + 3.0)\ A_{x,f}/w_a \tag{9}$$

The value of $A_{x,f}/w_a$ is determined from the air temperature, pressure, and M_2.

It should be pointed out that the range of operating variables investigated includes cases where the steam temperatures into the exchanger are too high for aluminum fins to be used. Where steel fins are used, the exchanger configuration would be changed markedly (optimum fin width and spacing would vary), and would also result in heavier exchangers. For the design-point operating conditions currently being considered for this cycle (T_A 1460° R and P_B about 1250 lb/sq in. or lower) an exchanger with aluminum fins can be used. In order to avoid the complication involved in varying the exchanger designs as conditions varied, the design described was fixed for the range of conditions investigated, which favors the performance at higher values of P_B.

Gear Weight

The weight of reduction gearing is largely a function of the power transmitted through the gears and the speed reduction ratio. For the cycle considered, both of these depend on the size and number of engines selected. In the analysis the effect of size and number of engines and their configuration in the airplane was not studied; instead, a value of gear weight of 0.10 lb/hp was assumed. This value is representative of what is being currently obtained for gearing rated at about 10,000 hp and about 10 to 11 speed reduction ratios.

Turbine and Condensate Pump Weights

The turbine and the condensate pump will be relatively small in size. Their weights were assumed to vary with the number of stages and amount of steam handled; the relationship used for the combined weights is

$$W_{t+p}/w_s = 8.0 \log_e P_A/P_B \tag{10}$$

The value of the constant is based on estimates of size, power transmitted, and some values of weights given in reference 5.

Reactor, Shield, and Auxiliary Weights

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In the analysis a group of weights W_k is considered to be nearly independent of the size of the airplane and design-point operating conditions. In this group are included the weights of the reactor and shield assembly, the pay load, the piping, the water used as cycle fluid, the controls, and the accessory equipment. A constant value of W_k equal to 150,000 pounds has been assumed in order to evaluate W_g, Q_r, w_a, A_c, and A_x. This value of W_k is based on a reactor core diameter of about 2.5 feet, this size assumed to remain constant as power varies (sufficiently high heat flux rates and heat-transfer surface to handle the range in reactor heat release without excessive temperatures are assumed obtainable within this volume). The performance values vary directly with W_k so that they can very easily be determined at any other values of W_k.

Airplane Structural Weight

The ratio W_s/W_g was assumed constant as the size and weight of the airplane varies. A value of W_s/W_g equal to 0.35 was chosen.

PERFORMANCE OF ENGINE AND AIRPLANE COMPONENTS

Engine Component Efficiencies

The efficiencies listed are representative of the values obtained in current practice. For the components which require considerable development (such as the steam turbine and condensate pump) these efficiencies are optimistic values.

Compressor efficiency, η_c 0.88
Steam turbine efficiency, η_t 0.85
Condensate pump efficiency, η_p 0.80
Exhaust nozzle velocity coefficient, C_v 0.98
Inlet diffuser total pressure ratio, P_1/P_0
  at 0.9 flight Mach number 0.975
  at 1.5 flight Mach number 0.95

Gear losses were neglected.

Heat-Exchanger Performance

Both heat-transfer and pressure-drop calculations are based on the assumption that the air passages between fins are smooth tubes.

The resistance of the steam film is neglected; this assumption is more accurate for condensing steam. The resistance of the direct heating surface (which is the surface in contact with the steam) is also neglected. However, the resistance of the fins is accounted for by evaluating a fin effectiveness which in turn is used to evaluate a constant effective wall temperature around any cross section in the air flow passage. 2593

Exchanger calculations are based on the assumption of counterflow during the heat transfer from superheated steam to air. The pressure drops evaluated are increased arbitrarily by 15 percent to account for pressure losses involved in bending of the air flow when entering and leaving the exchanger. Bending of the air stream is required because, in general, the frontal area of the exchangers is larger than that of the compressor and the exchanger must be inclined to fit behind the compressor (see fig. 1).

Aerodynamic Performance

At supersonic flight speeds, L/D_W and L/D_{tot} will vary with airplane size (particularly if the airplane and engine configuration depends on airplane size). In the analysis, the more simplifying assumption was used that L/D_{tot} remains constant as the airplane size (which is a function of engine design point operating conditions) varies. This assumption was made for all flight conditions investigated. However, several values of L/D_{tot} were chosen at each set of design flight conditions.

APPENDIX B

SAMPLE CALCULATION

To illustrate the method of calculation, the performance of the cycle operating at the following given design-point flight and engine operating conditions is determined:

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Flight Mach number	1.5
Altitude, ft	50,000
T_A, $^{\circ}R$	1460
P_A, lb/sq in.	5000
P_B, lb/sq in.	1250
P_D, lb/sq in.	5050
P_2/P_1	1.214
M_2	0.20
η_c	0.88
η_t	0.85
η_p	0.80
C_v	0.98
Diffuser pressure ratio	0.95

Assume values of

L/D_{tot}	5
W_s/W_g	0.35
W_k, lb	150,000
$\frac{w_a \sqrt{T_1/519}}{A_c \; P_1/2116}$, $\frac{\text{lb/sec}}{\text{sq ft}}$	25.0

EVALUATION OF F/w_a

Steam Cycle Calculations

From P_A, T_A, P_B, and η_t using the steam tables (ref. 6),

$$\Delta H_t/w_s = 122.6 \text{ Btu/lb}$$

$$T_B = 1089^{\circ} \text{ R}$$

T_{sat} corresponding to $P_B = 1032^\circ$ R

$T_C = T_{sat} - 20 = 1012^\circ$ R

From T_B, T_{sat}, and T_C using the steam tables:

Heat release during condensation = 628.5 Btu/lb

Heat release from superheat to saturated condition = 65.9 Btu/lb

Total Q_x/w_s = 694.4 Btu/lb

The pump compresses the condensate to a pressure P_D of 5050 pounds per square inch. From the values of T_C, P_C (assumed the same as P_B), P_D, and η_p, using figure III of the steam tables

$\Delta H_p/w_s$ = 19.1 Btu/lb

From enthalpy values at pump outlet and reactor outlet,

Q_r/w_s = 797.9 Btu/lb

The net work out of steam cycle = $\Delta H_t/w_s - \Delta H_p/w_s$ = 103.5 Btu/lb.

Air Cycle Calculations

From flight conditions and diffuser pressure recovery

V_0 = 1457 ft/sec

$T_1 = 570^\circ$ R

$P_1/p_0 = 3.487$

P_1 = 845 lb/sq ft

From P_2/P_1, T_1, and η_c using the air tables (ref. 7)

$\Delta H_c/w_a$ = 8.86 Btu/lb

$T_2 = 607^\circ$ R

P_2 = 1026 lb/sq ft

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neglecting gear losses

$$w_a \left(\frac{\Delta H_c}{w_a}\right) = w_s \left(\frac{\Delta H_t}{w_s} - \frac{\Delta H_p}{w_s}\right)$$

$$\frac{w_a}{w_s} = \frac{122.6 - 19.1}{8.86} = 11.68$$

From exchanger heat balance

$$\frac{Q_x}{w_a} = \frac{w_s}{w_a}\frac{Q_x}{w_s} = \frac{694.4}{11.68} = 59.40\ \frac{\text{Btu/sec}}{\text{lb/sec}}$$

then using Q_x/w_a, and T_2, from the air tables

$$T_3 = 852^{\circ}\ R$$

This is an attainable operating condition because T_3 is less than T_B.

The determination of P_3 requires evaluating the heat-exchanger performance.

Heat-Exchanger Calculations

The exchanger is considered as made up of two exchangers in series. In the first, air enters at a Mach number of 0.20 and is heated by the condensing steam; in the second, the air is further heated by superheated steam (counterflow assumed).

The mass flow of air per unit flow area through the exchanger can be expressed as

$$\frac{w_a}{A_{x,f}} = \sqrt{\frac{\gamma g}{R}}\ \frac{(M_2)}{\left[1 + \frac{\gamma-1}{2}(M_2)^2\right]^{\frac{\gamma+1}{2(\gamma-1)}}}\ \frac{P_2}{\sqrt{T_2}}$$

where:

γ ratio of specific heats of air = 1.4

g acceleration due to gravity = 32.2 ft/sec^2

R gas constant for air = 53.3 Btu/lb $^{\circ}$F so

$$\frac{w_a}{A_{x,f}} = \sqrt{\frac{1.4\times32.2}{53.3}}\ \frac{0.20}{\left[1 + (0.2)^2\left(\frac{1.4-1}{2}\right)\right]^3}\ \frac{1026}{\sqrt{607}} = 7.48\ \frac{\text{lb/sec}}{\text{sq ft}}$$

Condensing exchanger calculations: evaluation of l/d. - The temperature of the air after being heated by condensing steam can be determined from T_2, the heat transferred from the condensing steam per pound of air (628.5/11.68 = 53.81), and the air tables (ref. 7) 2593

$$T_2' = 829^\circ\ R$$

The average bulk temperature of the air in the exchanger is

$$T_b = \frac{1}{2}(T_2' + T_2) = \frac{1}{2}(829 + 607) = 718^\circ\ R$$

The wall temperature = T_{sat} = 1032° R

The following properties of air at wall temperature are evaluated from table III in the air tables (ref. 7)

Viscosity, μ, lb/ft-sec	196×10^{-7}
Conductivity, k, Btu/sec-ft-°F	74×10^{-7}
Specific heat, c_p, Btu/lb-°F	0.250
Prandtl number, Pr	0.66

Using these values in the equation

$$h = 0.023\ \frac{k}{d}\left(\frac{\frac{w_a}{A_{x,f}}\ d}{\mu}\right)^{0.8}\left(\frac{T_b}{T_w}\right)^{0.8}(Pr)^{0.4}$$

$$h = 0.00774\ \frac{\text{Btu}}{\text{sec-ft}^2\ {}^\circ\text{F}}$$

In the exchanger fins there is less heat transferred per unit fin surface than through a unit of direct heating surface. The fin effectiveness is the ratio of these rates of heat flow and can be expressed as the ratio of the effective temperature difference between the fin surface and fluid to the available temperature difference between the direct heating surface and the fluid.

A factor is defined:

$$\phi = \frac{(\text{fin width})}{2}\sqrt{\frac{2\times(\text{heat transfer coefficient between fin and air})}{(\text{conductivity of fin})(\text{thickness of fin})}}$$

then the fin effectiveness η_f is $\dfrac{\tanh \phi}{\phi}$

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In the exchanger considered, aluminum fins 0.01 inch thick, 0.75 inch wide, having an average value of conductivity of 125 Btu/hr-ft-°F, were selected.

From these values and the value of h previously determined, the value $\eta_f = 0.85$ is obtained.

The rectangular air flow passage in the exchanger has fins on two sides and direct heating surfaces on the other two sides. The fins are 0.75 inch wide, while the direct heating surfaces are 0.0733 inch long between fins. The effective wall temperature of the passage is considered constant around the whole perimeter of the passage and is evaluated from the expression

$$(T_{w,eff} - T_b)(0.0733 + 0.75) = (T_w - T_b)\ 0.0733 + (T_w - T_b)\ 0.75\ \eta_f$$

so that

$$T_{w,eff} - T_b = (T_w - T_b)\left(\frac{0.0733 + 0.75\ \eta_f}{0.0733 + 0.75}\right)$$

In the condensing exchanger the wall temperature is considered to be equal to T_{sat} at all points (neglecting the effect of subcooling). At the exchanger inlet where the bulk air temperature is T_2, the effective temperature difference $= (1032 - 607)\ \dfrac{0.0733 + 0.85 \times 0.75}{0.0733 + 0.75} = 367^\circ$ F. Similarly, at the outlet where the bulk air temperature is T_2', the effective temperature difference $= (1032 - 829)\ \dfrac{0.0733 + 0.85 \times 0.75}{0.0733 + 0.75}$ $= 175^\circ$ F. The log mean temperature difference $= \dfrac{367 - 175}{\log_e \frac{367}{175}} = 259^\circ$ F.

From this value and the average value of heat-transfer coefficient,

$$\frac{l}{d} = \frac{\left(\frac{w_a}{A_{x,f}}\right)\left(\frac{Q}{w_a}\right)}{4(\text{log mean temperature difference})h} = \frac{7.48\times\left(\frac{628.5}{11.68}\right)}{4 \times 259 \times 0.00774} = 50.4$$

Condensing exchanger calculations: evaluation of pressure drop. - An equivalent constant wall temperature $T_{w,equ}$ is determined so that the log mean temperature difference obtained from $T_{w,equ} - T_2$ and $T_{w,equ} - T_2'$ is the same as that previously determined. Thus,

$$\frac{(T_{w,equ} - T_2) - (T_{w,equ} - T_2')}{\log_e \dfrac{T_{w,equ} - T_2}{T_{w,equ} - T_2'}} = \text{log mean temperature difference} = 259^\circ \text{ F}$$

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from which

$$T_{w,equ} = 993^\circ \text{ R}$$

Then

$$\frac{T_2}{T_{w,equ}} = \frac{607}{993} = 0.611$$

$$\frac{T_2'}{T_{w,equ}} = \frac{829}{993} = 0.835$$

From the constant wall pressure drop chart presented in reference 2, the pressure ratio across the exchanger is equal to 0.937. This results in a pressure out of the exchanger equal to 961 lb/sq ft. In the expression for $w_a/A_{x,f}$ using this value of total pressure and values of T_2' equal to 829° R and $w_a/A_{x,f}$ of 7.48 lb/(lb/sec), a value of Mach number at exchanger outlet equal to 0.255 is determined.

Superheat exchanger calculations: evaluation of l/d. - For the given cycle operating conditions selected, the amount of heat released by the superheat portion of the steam is slight.

From T_2' and T_3 the average bulk temperature

$$T_b = \frac{1}{2}(829 + 852) = 840^\circ \text{ R}$$

From T_{sat} and T_B the average wall temperature

$$T_w = \frac{1}{2}(1032 + 1089) = 1060^\circ \text{ R}$$

The air properties evaluated at the average wall temperature are essentially the same as previous values. The mass flow of air per unit flow area remains constant so that

$$h = 0.023 \, \frac{74\times10^{-7}}{0.01113} \left(\frac{7.48\times0.01113}{196\times10^{-7}}\right)^{0.8} \left(\frac{840}{1060}\right)^{0.8} (0.66)^{0.4}$$

$$= 0.00859 \, \frac{\text{Btu}}{\text{sec-ft}^2 \, {}^{\circ}\text{F}}$$

The fin effectiveness at this value of h becomes 0.84. The temperature difference at inlet $= (1032 - 829) \dfrac{(0.0733 + 0.75 \times 0.84)}{0.0733 + 0.75} = 173^{\circ}$ F. The temperature difference at outlet $= (1089 - 852) \left(\dfrac{0.0733 + 0.75 \times 0.84}{0.0733 + 0.75}\right)$ $= 202^{\circ}$ F. The log mean temperature difference $= \dfrac{202 - 173}{\log_e \dfrac{202}{173}} = 187$.

$$l/d = \frac{7.48 \times \left(\frac{65.9}{11.68}\right)}{4 \times 187 \times 0.00859} = 6.6$$

Superheat exchanger calculations: evaluation of pressure drop. - When used with $T_2' = 829^{\circ}$ R and $T_3' = 852^{\circ}$ R, the following value of equivalent constant wall temperature results in a log mean temperature difference of 187° R:

$$T_{w,equ} = 1029^{\circ} \text{ R}$$

$$\frac{T_2'}{T_{w,equ}} = \frac{829}{1029} = 0.806$$

$$\frac{T_3}{T_{w,equ}} = \frac{852}{1029} = 0.828$$

The inlet Mach number of air to this exchanger is the same as the outlet Mach number of the first exchanger and is equal to 0.255.

Again by use of the pressure drop chart, a value of pressure ratio across the second exchanger of 0.989 is determined from these values.

Over-all exchanger performance. - The over-all l/d of the exchanger = 50.2 + 6.6 = 56.8.

The over-all pressure ratio is 0.989 × 0.937 = 0.927. An additional 15 percent of the pressure drop is added for losses in bending the air flow into and out of the exchanger.

The entire pressure drop $\Delta P/P_2 = 1.15 \times (1 - 0.927) = 0.084$. Therefore, $P_3/P_2 = 1 - 0.084 = 0.916$. The pressure ratio across the exhaust nozzle

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$$\frac{P_3}{p_0} = \frac{P_1}{p_0}\frac{P_2}{P_1}\frac{P_3}{P_2} = (3.487)(1.214)(0.916) = 3.877$$

From the values of P_3/p_0, T_3, and C_v, and from the air tables,

$$V_j = 1778 \text{ ft/sec}$$

$$F/w_a = \frac{1778 - 1457}{32.2} = 9.97 \text{ lb/(lb/sec)}$$

EVALUATION OF F/W_e

From equation (8)

$$\frac{W_c}{w_a} = 84.8\frac{\sqrt{T_1}}{P_1} = \frac{84.8\sqrt{570}}{845} = 2.40 \frac{\text{lb}}{(\text{lb/sec})}$$

From equation (9)

$$\frac{W_x}{w_a} = \left(0.595\frac{l}{d} + 3.0\right)\frac{A_{x,f}}{w_a} = \frac{0.595 \times 56.8 + 3.0}{7.48} = 4.92 \frac{\text{lb}}{\text{lb/sec}}$$

From equation (10)

$$\frac{W_{t+p}}{w_a} = \frac{W_{t+p}}{w_s}\frac{w_s}{w_a} = \frac{w_s}{w_a} 8.0 \log_e \frac{P_A}{P_B} = \frac{8.0}{11.68}\log_e 4 = 0.95 \frac{\text{lb}}{(\text{lb/sec})}$$

Assuming the horsepower transmitted through the gears is equal to turbine horsepower output, then

$$\frac{W_b}{w_a} = 0.10\frac{hp_t}{w_a} = 0.10\frac{\Delta H_t}{w_s}\frac{w_s}{w_a}\frac{778}{550} = 0.10 \times \frac{122.6}{11.68} \times \frac{778}{550} = 1.48 \frac{\text{lb}}{(\text{lb/sec})}$$

$$\frac{W_e}{w_a} = 1.48 + 0.95 + 4.92 + 2.40 = 9.75\ \frac{\text{lb}}{(\text{lb/sec})}$$

$$F/W_e = \frac{9.97}{9.75} = 1.023\ \frac{\text{lb}}{\text{lb}}$$

EVALUATION OF OTHER PERFORMANCE PARAMETERS

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Gross Weight

The gross weight of the airplane is determined from equation (1a)

$$W_g = \frac{150{,}000}{1 - 0.35 - \dfrac{1}{5 \times 1.023}} = 330 \times 10^3\ \text{lb}$$

Air Flow Rate

The air flow can be expressed as

$$w_a \equiv \frac{F}{F/w_a} = \frac{W_g \dfrac{D}{L_{tot}}}{F/w_a}$$

by equation (1a), w_a can be written as

$$w_a = \frac{W_k}{\dfrac{L}{D_{tot}} \dfrac{F}{w_a}\left(1 - \dfrac{W_s}{W_g}\right) - \dfrac{W_e}{w_a}} = \frac{150{,}000}{5 \times 9.97\ (1 - 0.35) - 9.75} = 6620\ \frac{\text{lb}}{\text{sec}}$$

Steam Flow Rate

$$w_s = w_a \frac{w_s}{w_a} = \frac{6620}{11.68} = 567\ \frac{\text{lb}}{\text{sec}}$$

Reactor Heat Release Rate

$$Q_r = w_s \frac{Q_r}{w_s} = 797.9 \times 567 = 452 \times 10^3\ \frac{\text{Btu}}{\text{sec}}$$

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Engine Component Weights

Compressor weight:

$$W_c = \left(\frac{W_c}{w_a}\right) w_a = 2.40 \times 6620 = 15{,}900 \text{ lb}$$

Exchanger weight:

$$W_x = \left(\frac{W_x}{w_a}\right) w_a = 4.92 \times 6620 = 32{,}500 \text{ lb}$$

Turbine and condensate pump weight:

$$W_{t+p} = \left(\frac{W_{t+p}}{w_a}\right) w_a = 0.95 \times 6620 = 6300 \text{ lb}$$

Gear box weight:

$$W_b = \frac{W_b}{w_a} w_a = 1.48 \times 6620 = 9800 \text{ lb}$$

Total engine weight:

$$W_e = 15{,}900 + 32{,}500 + 6{,}300 + 9{,}800 = 64{,}500 \text{ lb}$$

Compressor Frontal Area

$$A_c = \frac{w_a}{w_a/A_c}$$

$$\frac{w_a}{A_c} = \left(\frac{w_a\sqrt{\frac{T_1}{519}}}{A_c\ P_1/2116}\right)\frac{\sqrt{\frac{519}{T_1}}}{2116/P_1} = \frac{25.0\sqrt{\frac{519}{570}}}{\frac{2116}{845}} = 9.527\ \frac{\text{lb/sec}}{\text{sq ft}}$$

$$A_c = \frac{6620}{9.527} = 695 \text{ sq ft}$$

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Exchanger Area

$$A_x = \frac{A_{x,f}}{f} = \frac{w_a \dfrac{A_{x,f}}{w_a}}{f} = \frac{6620}{7.48 \times 0.65} = 1360 \text{ sq ft}$$

Turbine Power Output

$$hp_t = \frac{hp_t}{w_s} w_s = 122.6 \times \frac{778}{550} \times 567 = 98{,}300 \text{ hp}$$

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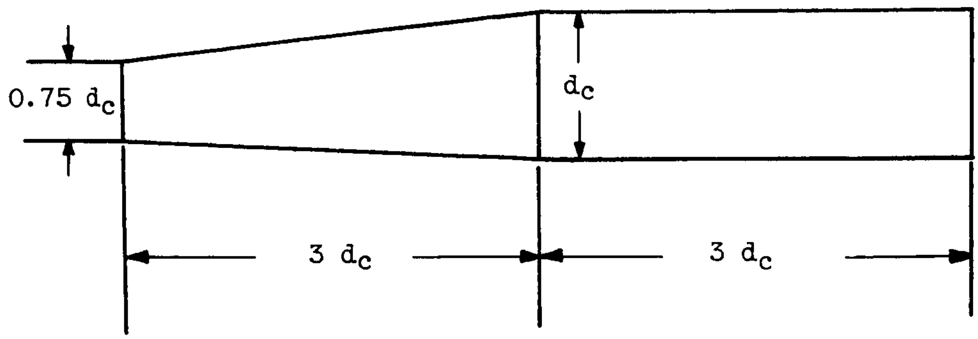
APPENDIX C

EVALUATION OF NACELLE DRAG



Evaluation of D_n/w_a

From data given in an NACA Conference on Aircraft Propulsion Systems Research (Jan. 18-19, 1950), for the assumed configuration and flight Mach number 1.5, and altitude 50,000 feet,

Wave drag coefficient for diffuser 0.0106
Friction drag coefficient 0.0025
Wave drag . . . . . . coefficient×maximum frontal area×dynamic pressure
Friction drag . . . . coefficient×surface area×dynamic pressure
Surface area of diffuser section . . . . 10.5 A_c
Surface area of straight section . . . . 12 A_c
Dynamic velocity head, lb/sq ft 382

$$\frac{\text{Drag on diffuser section}}{A_c} = 0.0106 \times 382 + 0.0025 \times 10.5 \times 382 = 14.1 \frac{\text{lb}}{\text{sq ft}}$$

$$\frac{\text{Drag on straight section}}{A_c} = 0.0025 \times 12 \times 382 = 11.5 \frac{\text{lb}}{\text{sq ft}}$$

$$\frac{\text{Total nacelle drag}}{A_c} = \frac{D_n}{A_c} = 25.6 \frac{\text{lb}}{\text{sq ft}}$$

$$\frac{w_a}{A_c} \text{ for flight conditions} = 9.53 \frac{\text{lb/sec}}{\text{sq ft}}$$

$$\frac{D_n}{w_a} = \frac{D_n}{A_c}\frac{A_c}{w_a} = \frac{25.6}{9.53} = 2.69 \frac{\text{lb}}{\text{lb/sec}}$$

This configuration was assumed to have a constant exhaust-nozzle area, whereas the nozzle area would actually vary with changes in operating conditions. The difference introduced in evaluating nacelle drag due to this assumption is very slight.

Expression for L/D_{tot} in Terms of $L/(D_w + D_t)$ and Nacelle Drag

2593 Neglecting fuselage drag,

$$\frac{D_{tot}}{L} = \frac{D_w + D_t}{L} + \frac{D_n}{L}$$

also,

$$D_n = \frac{D_n}{w_a} \frac{w_a}{F} D_{tot} \quad (\text{because} \quad D_{tot} = F)$$

so that,

$$\frac{D_{tot}}{L} = \frac{D_w + D_t}{L} + \frac{D_{tot}}{L} \frac{D_n}{w_a} \frac{w_a}{F}$$

and

$$\frac{L}{D_{tot}} = \frac{L}{D_w + D_t} \left(1 - \frac{D_n/w_a}{F/w_a}\right)$$

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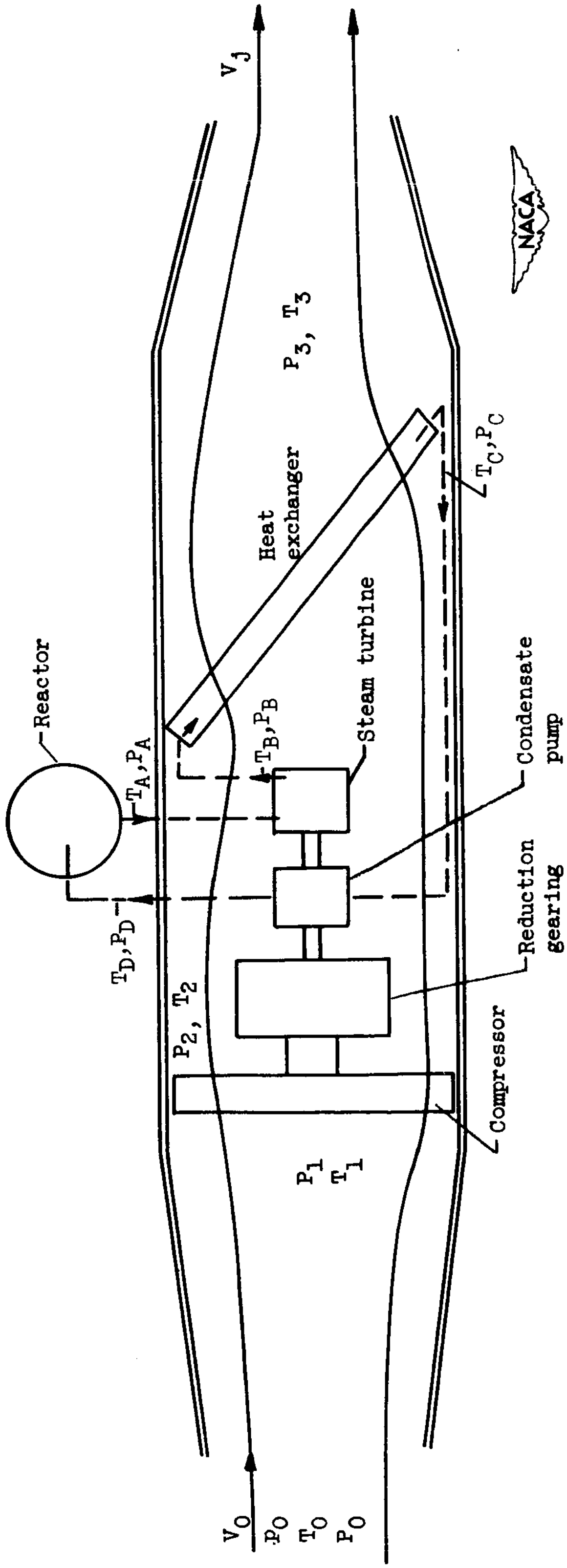

Figure 1. - Schematic diagram of supercritical-water-compressor jet cycle.

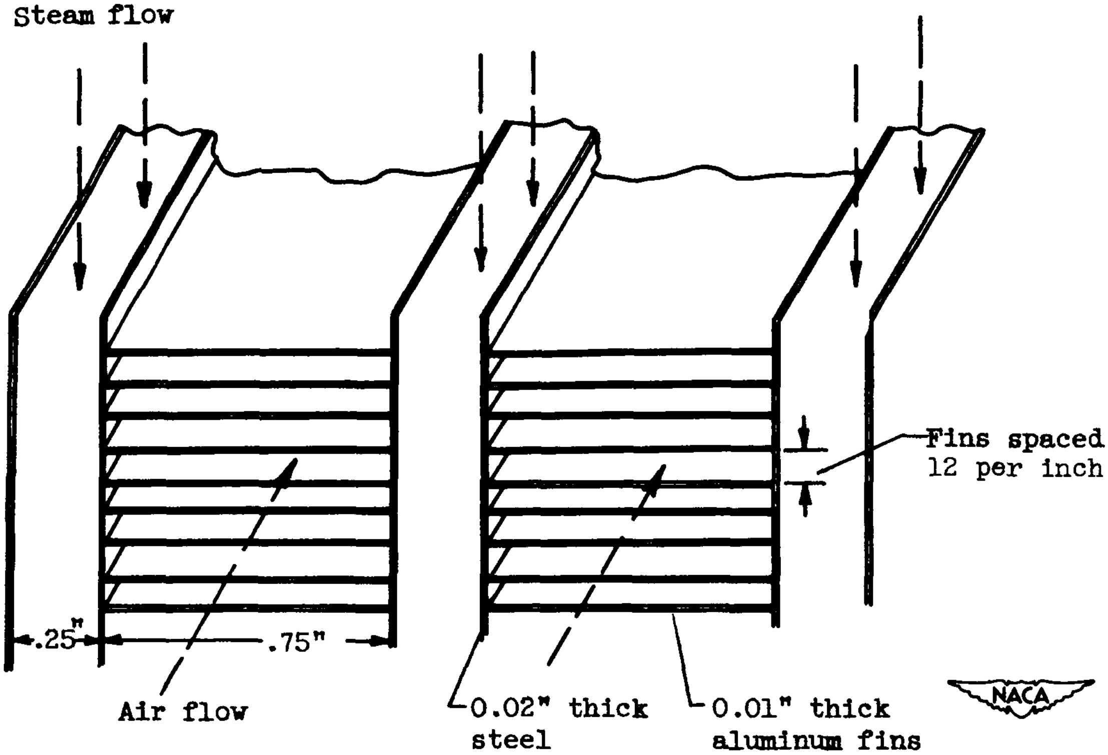

Figure 2. - Heat-exchanger configuration assumed for evaluation of exchanger weight, size, and pressure drop.

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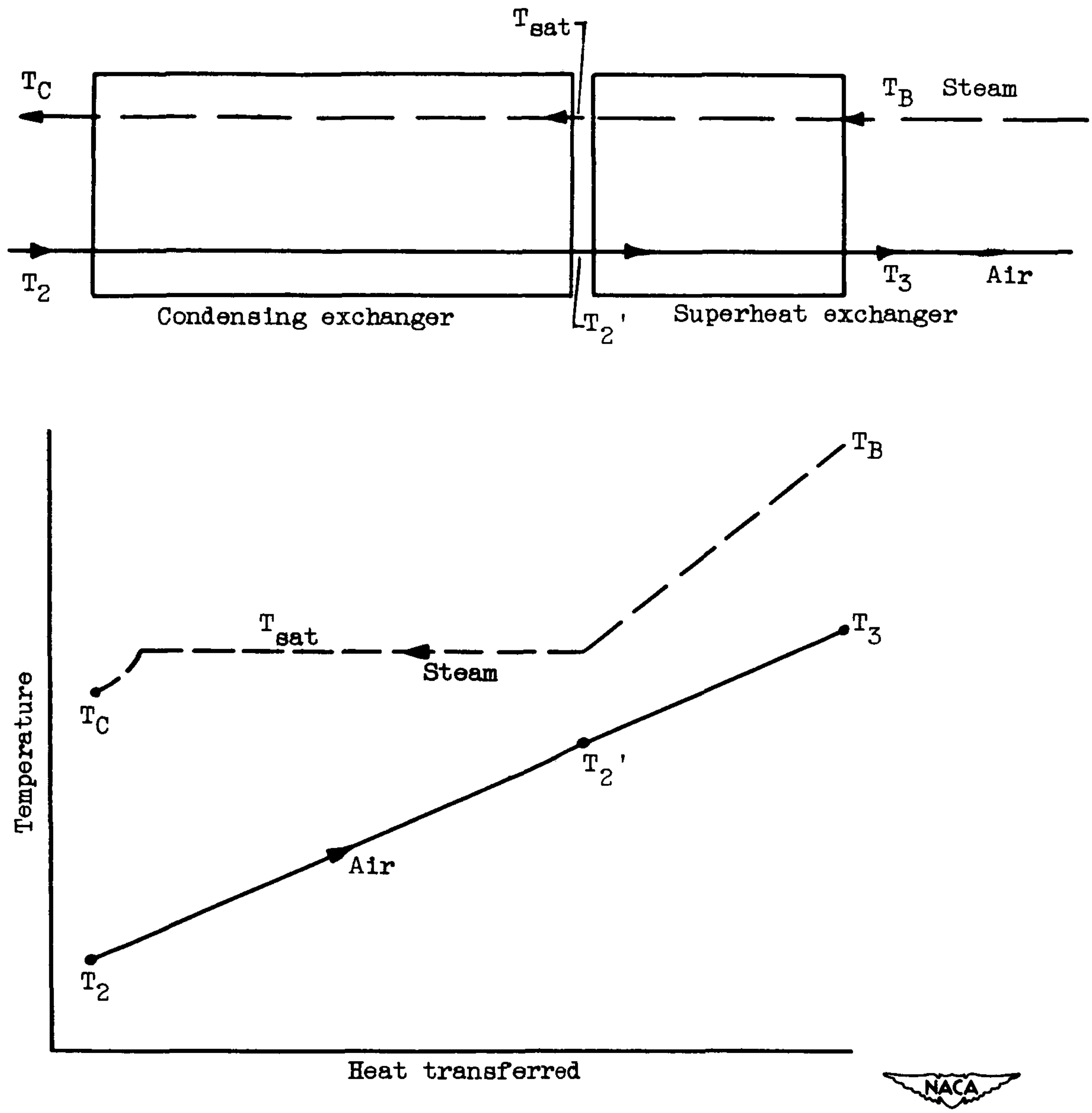
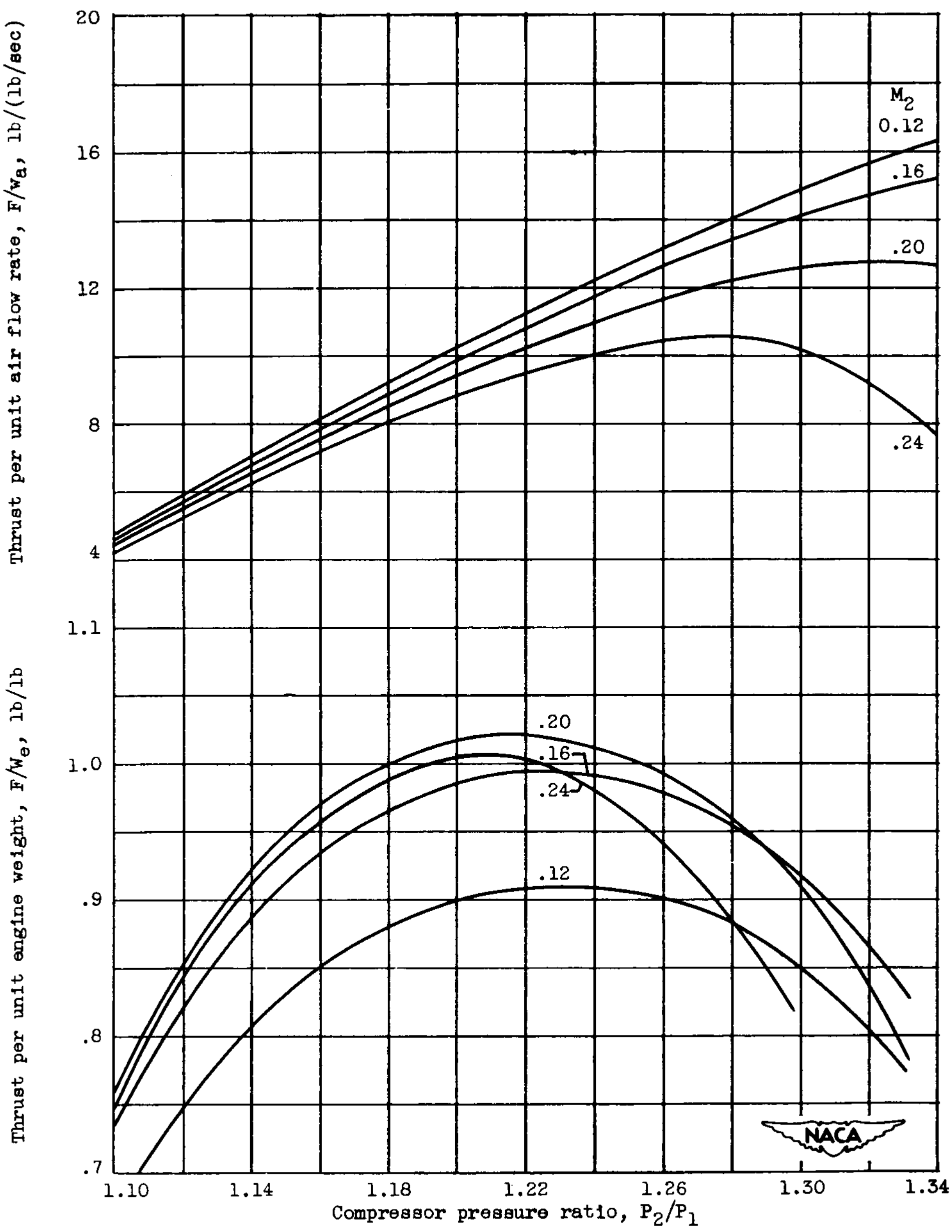


Figure 3. - Equivalent exchanger arrangement assumed for evaluating exchanger length-diameter ratio l/d and pressure drop when entering steam is superheated.



(a) F/W_e and F/w_a.

Figure 4. - Performance values of cycle at various values of P_2/P_1 and M_2. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; P_B, 1250 pounds per square inch.

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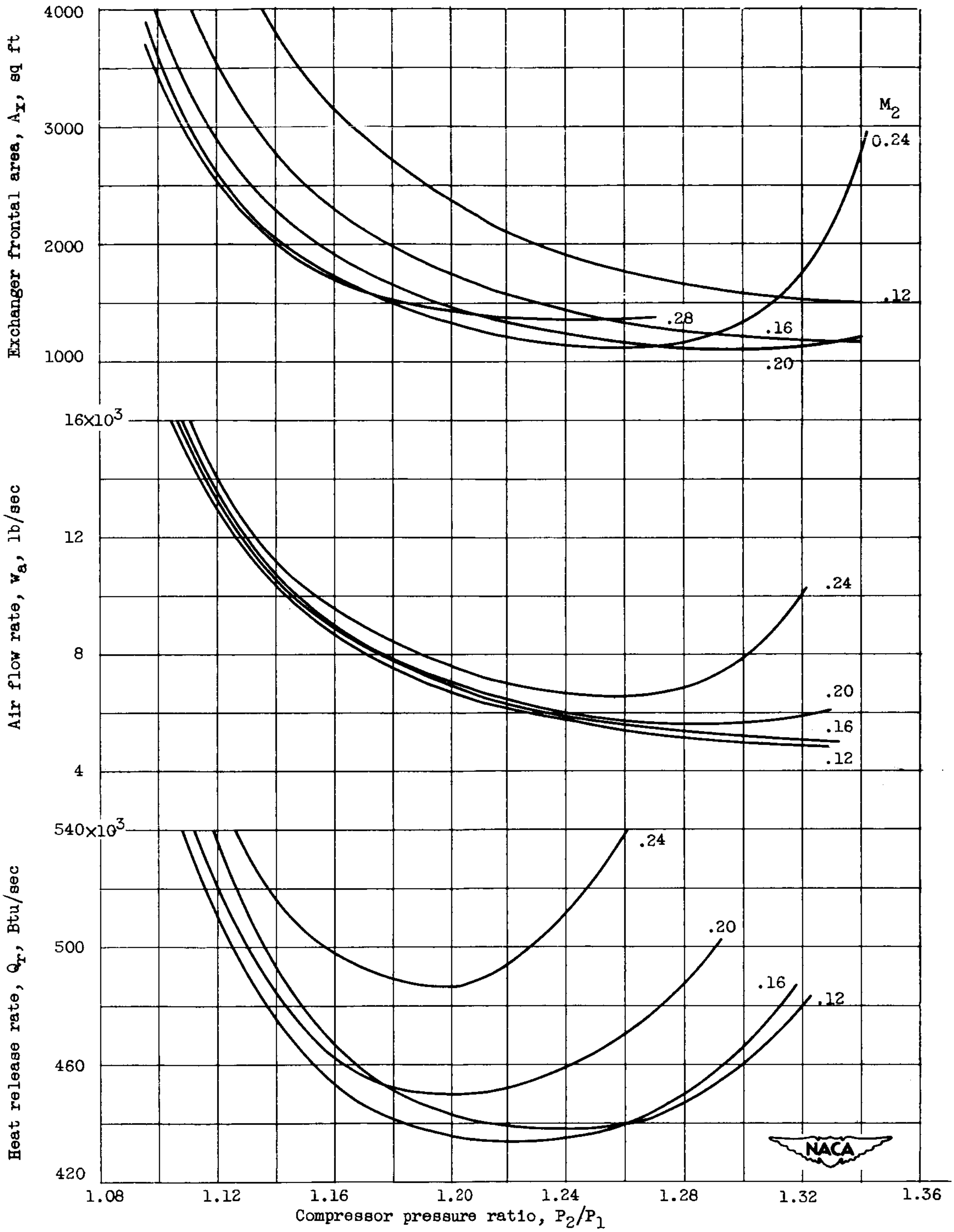
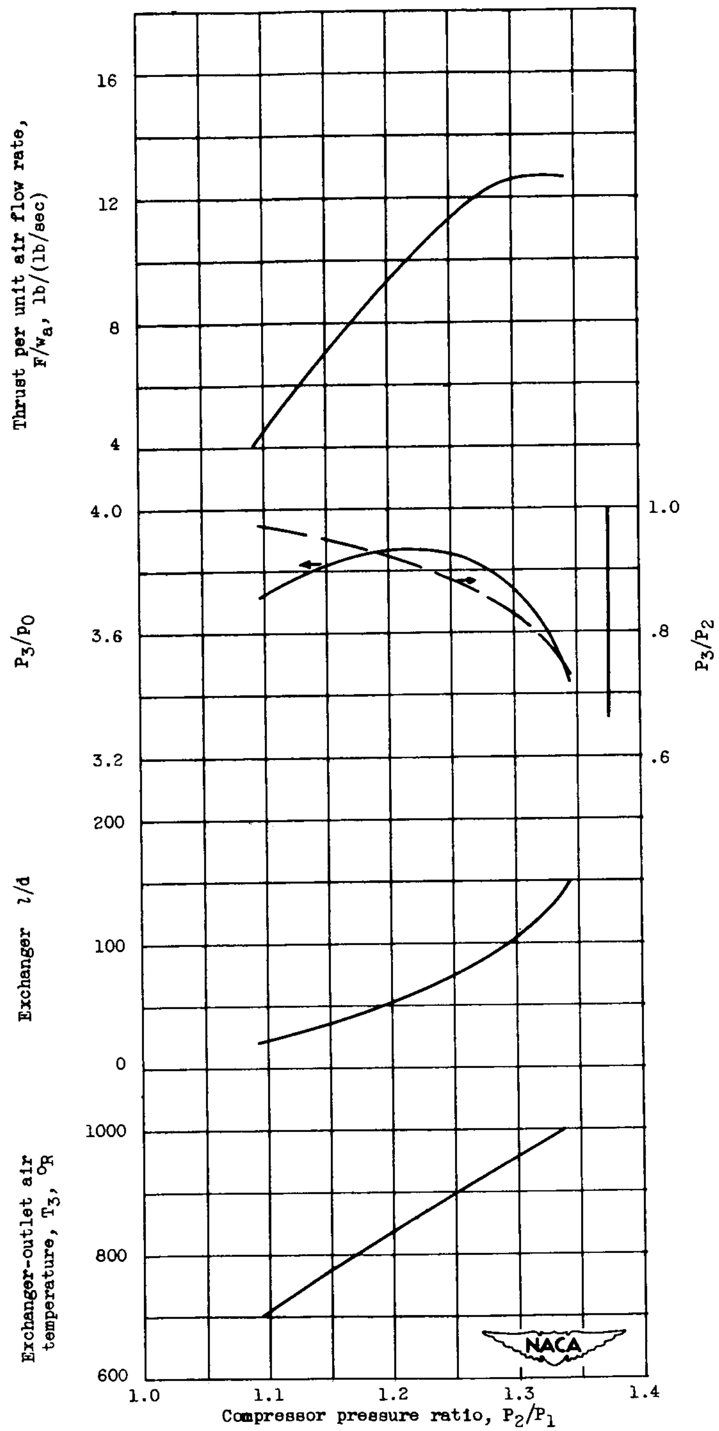


(b) Q_r, w_a, and A_x. W_s/W_g, 0.35; W_k, 150×10^3 pounds; L/D_{tot}, 5.

Figure 4. - Concluded. Performance values of cycle at various values of P_2/P_1 and M_2. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; P_B, 1250 pounds per square inch.



(a) Effect on T_3, l/d, P_3/P_2, P_3/p_0, and F/w_a.

Figure 5. - Effect of P_2/P_1 on engine components and over-all cycle performance. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; P_B, 1250 pounds per square inch; M_2, 0.20.

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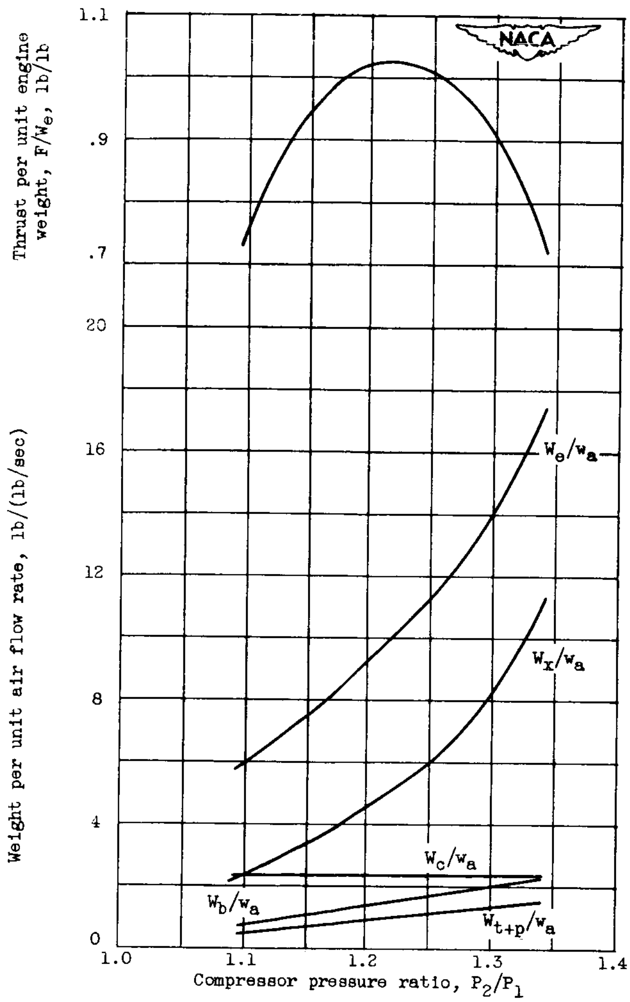
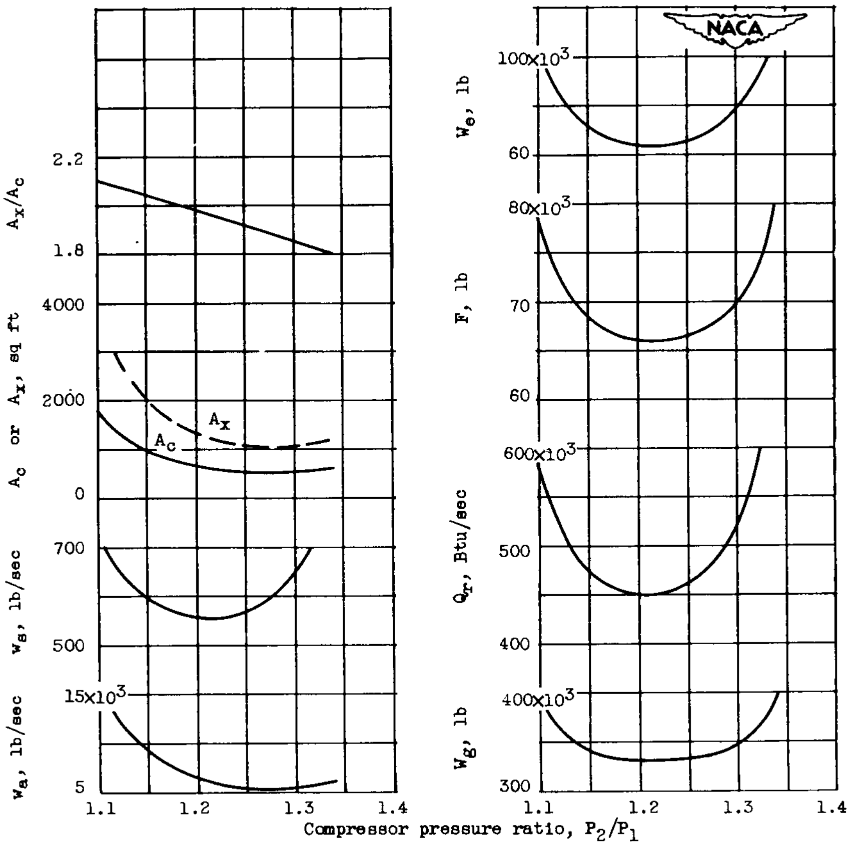


(b) Effect on engine and engine component weights and F/W_e.

Figure 5. - Continued. Effect of P_2/P_1 on engine components and over-all cycle performance. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; P_B, 1250 pounds per square inch; M_2, 0.20.



(c) Effect on W_g, Q_r, F, W_e, w_a, w_s, A_c, A_x, and A_x/A_c. W_s/W_g, 0.35; W_k, 150X10 pounds; L/D_{tot}, 5.

Figure 5. - Concluded. Effect of compressor pressure ratio on engine components and over-all cycle performance. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; P_B, 1250 pounds per square inch; M_2, 0.20.

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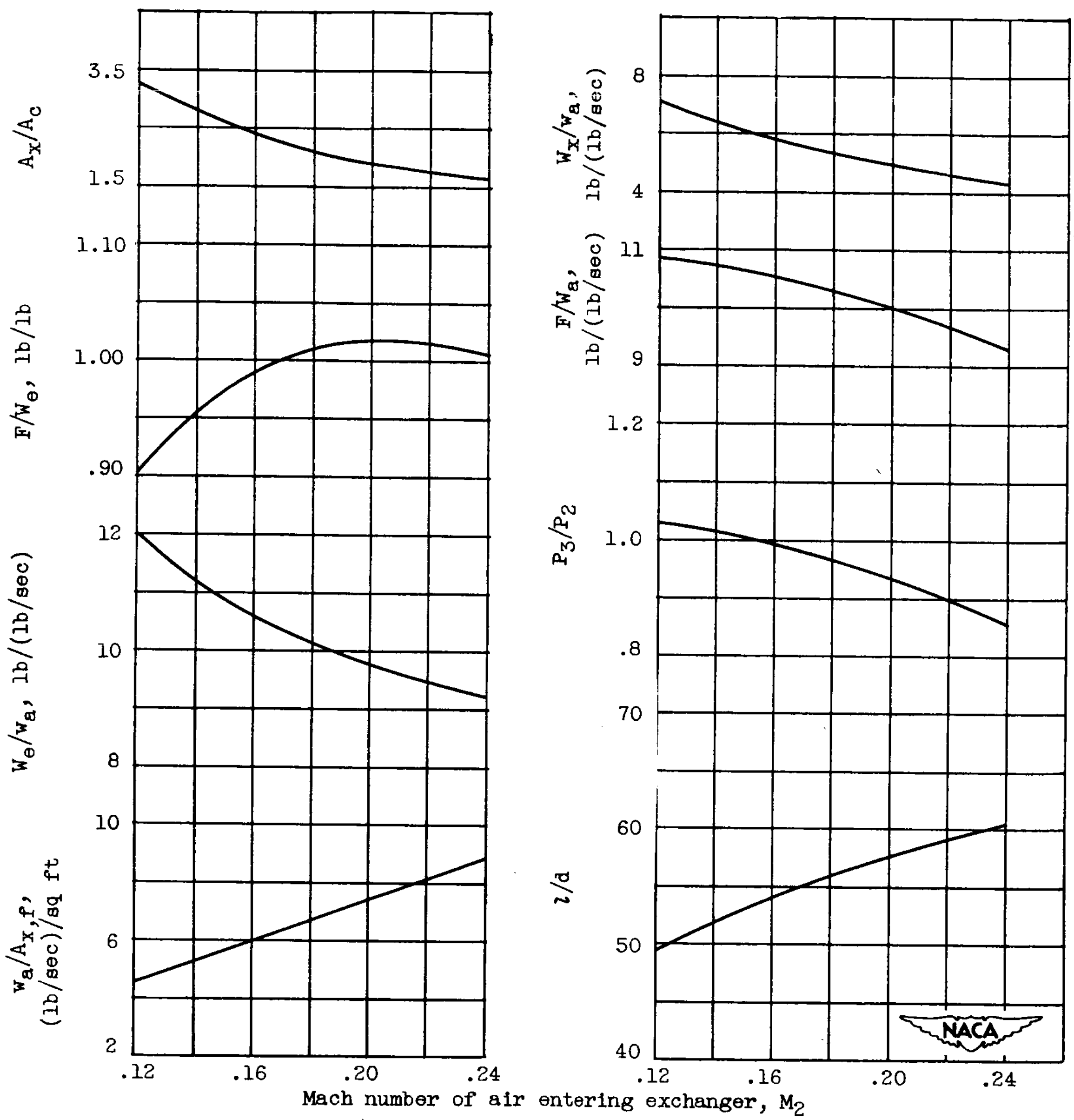

Figure 6. - Effect of M_2 on engine components and over-all cycle performance. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; P_B, 1250 pounds per square inch; P_2/P_1, 1.21.

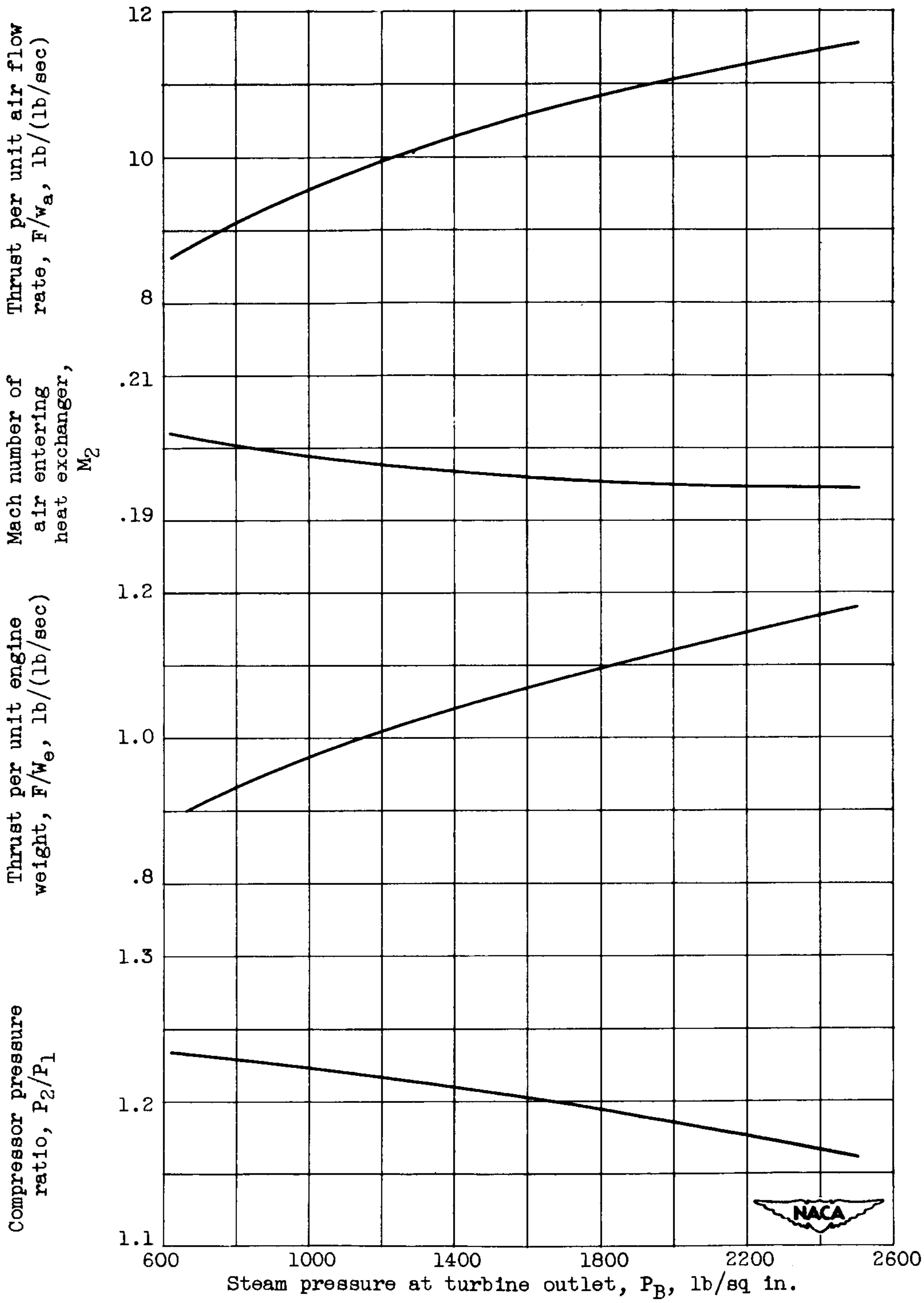

Figure 7. - Optimum values of P_2/P_1 and M_2 giving maximum F/W_e and corresponding values of F/W_e and F/w_a, for various values of P_B. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch.

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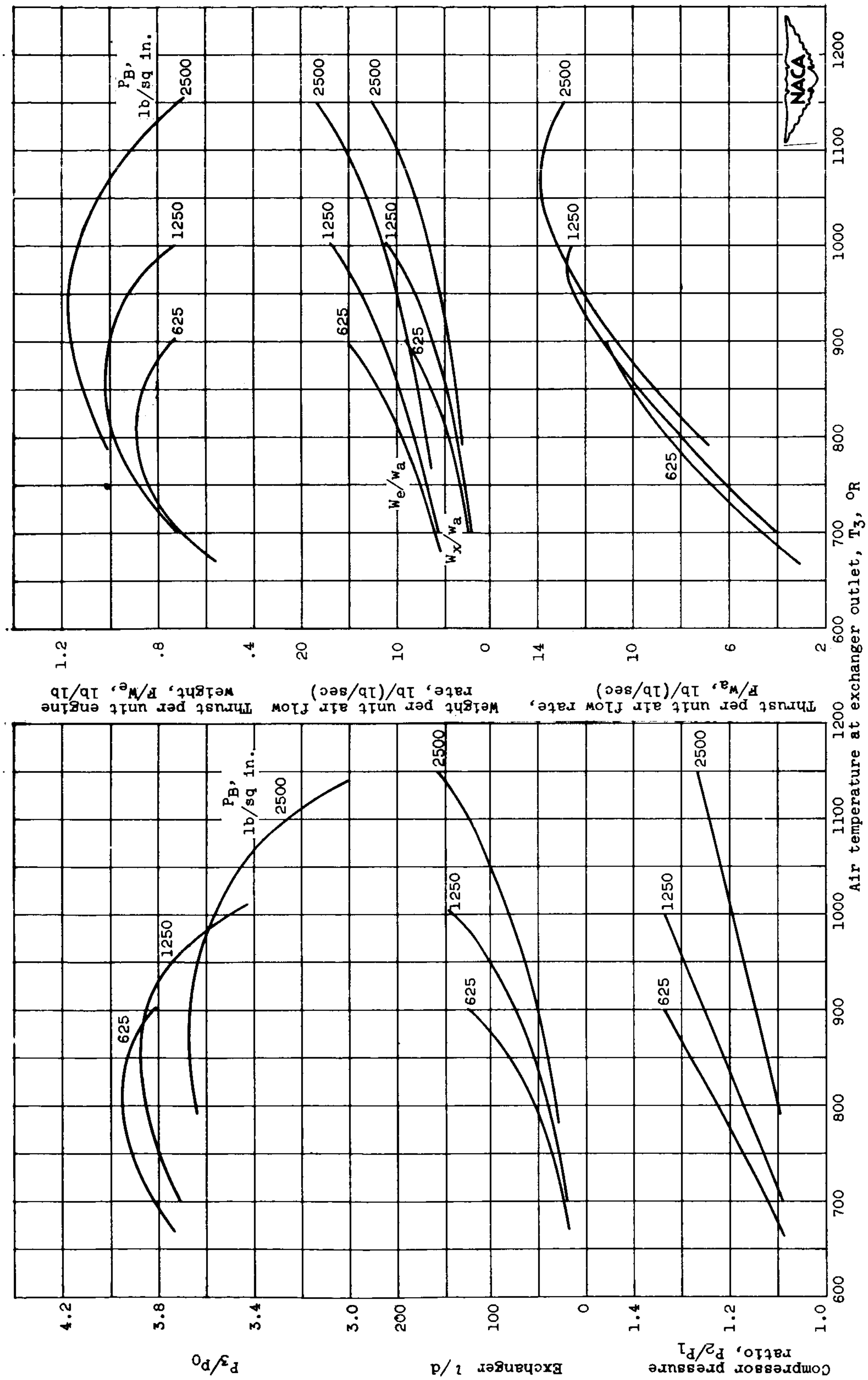
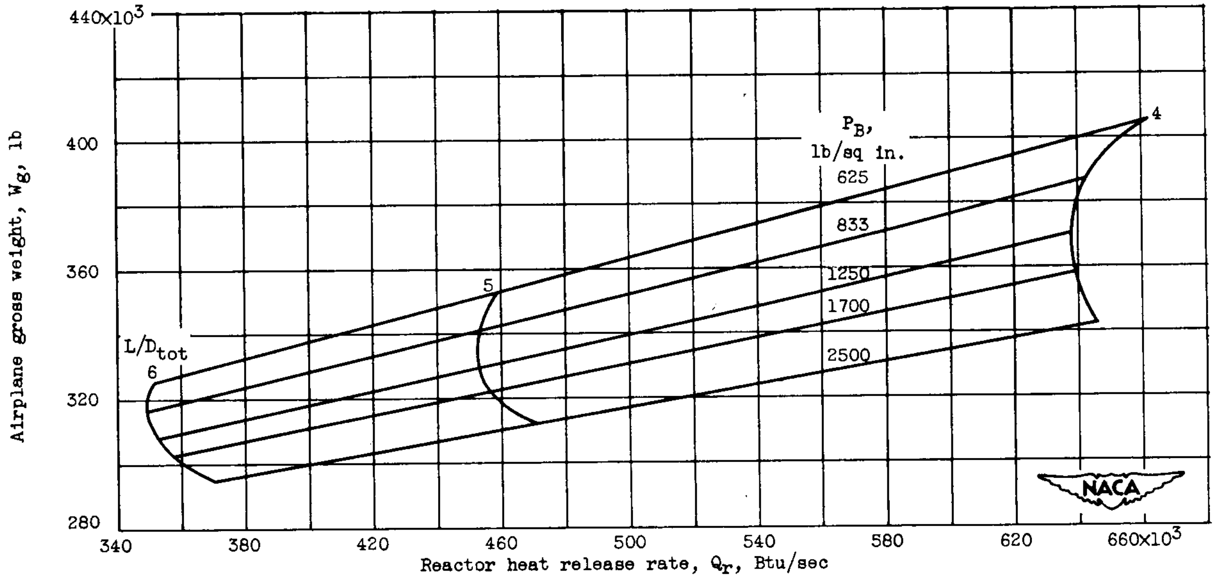


Figure 8. - Effect of P_B on engine components and over-all cycle performance. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch.



(a) W_g against Q_r.

Figure 9. - Performance at optimum P_2/P_1 and M_2 for various values of L/D_{tot} and P_B. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; W_s/W_g, 0.35; W_k, 150×10^3 pounds.

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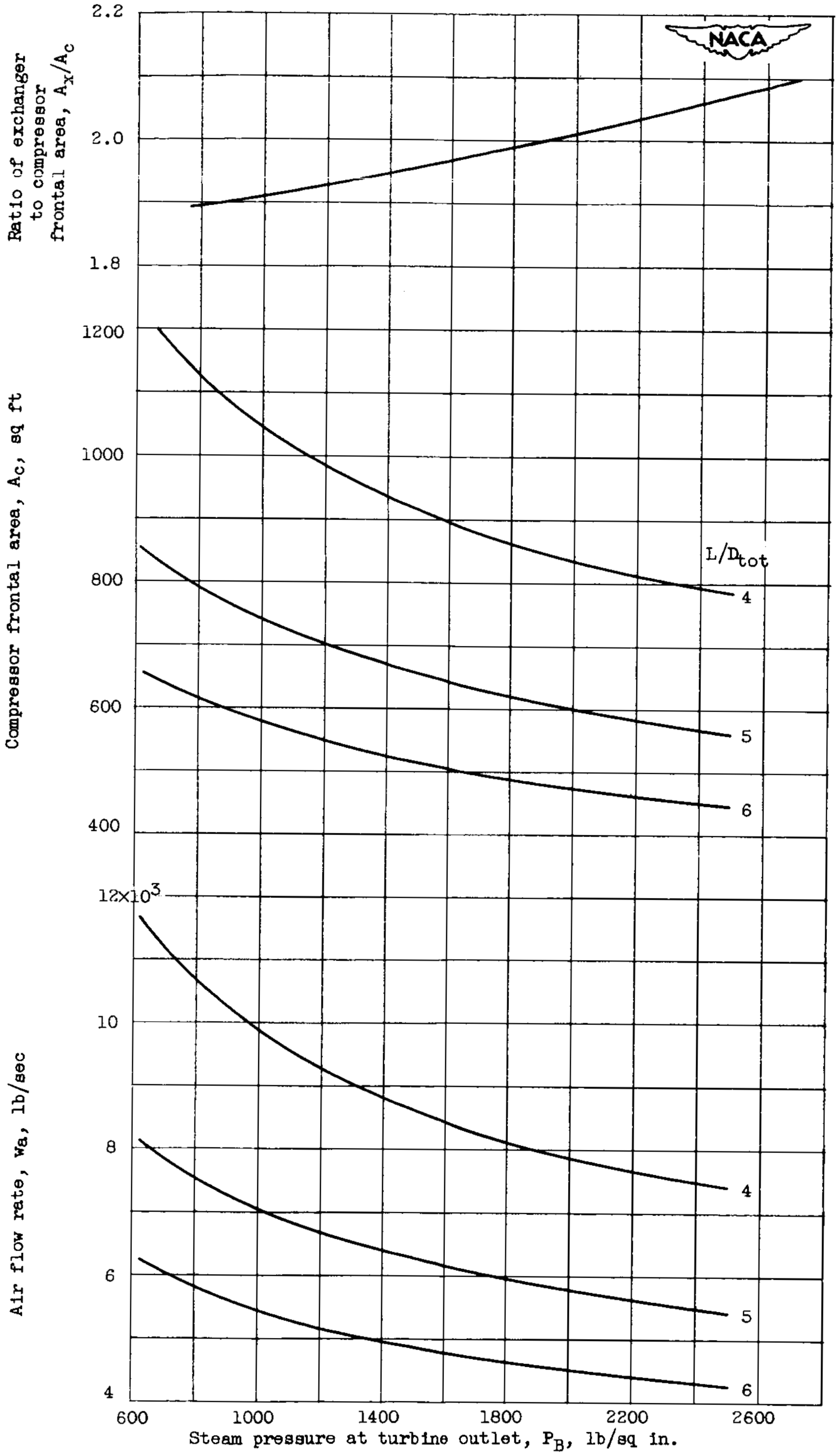

(b) Values of w_a, A_c, and A_x/A_c.

Figure 9. - Concluded. Performance at optimum P_2/P_1 and M_2 for various values of L/D_{tot} and P_B. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; W_s/W_g, 0.35; W_k, 150×10³ pounds.

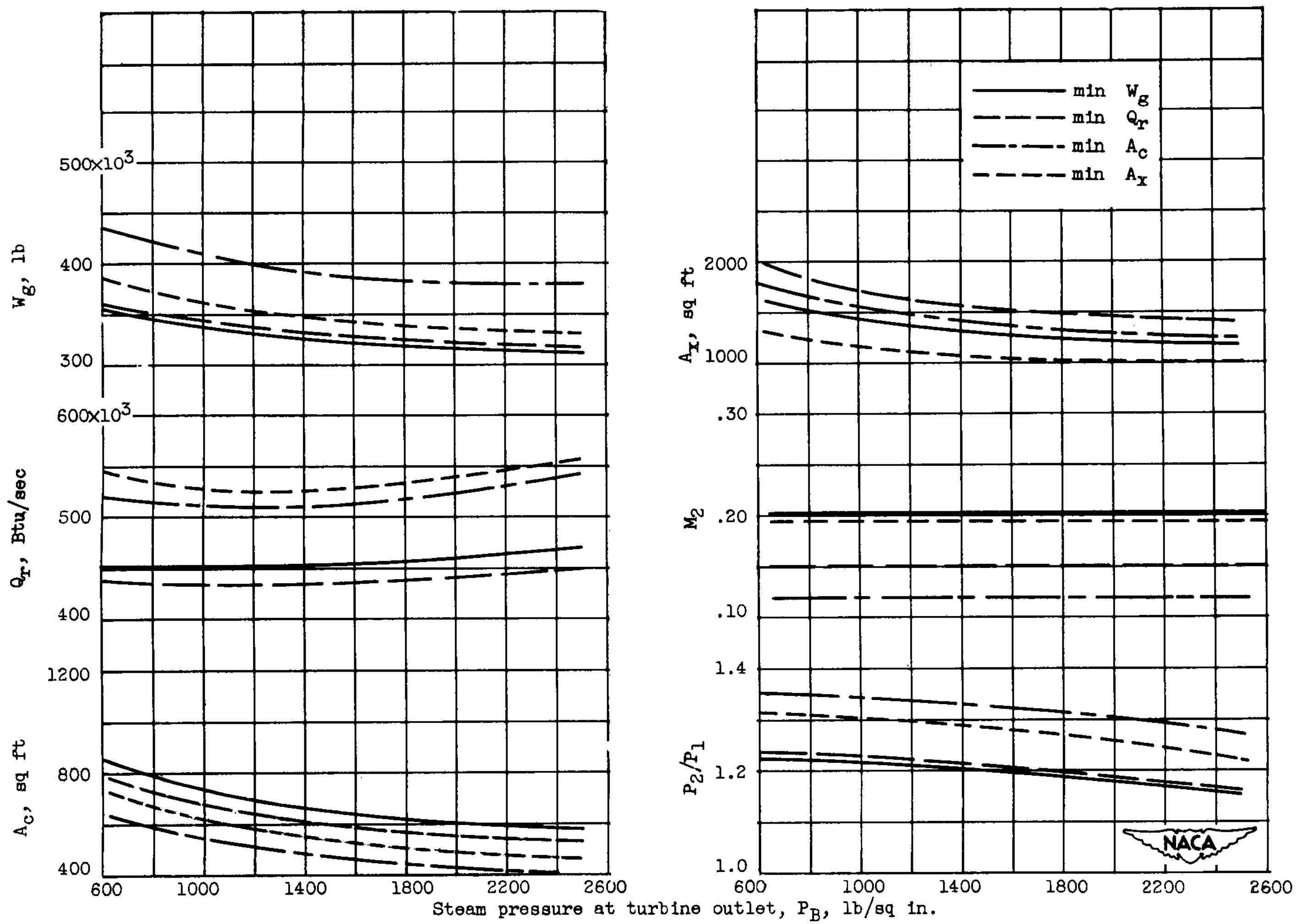

Figure 10. - Comparison of performances at P_2/P_1 and M_2 selected for minimum airplane gross weight, minimum reactor heat release rate, minimum compressor frontal area, and minimum exchanger frontal area. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; W_s/W_g, 0.35; W_k, 150,000 pounds; L/D_{tot}, 5.

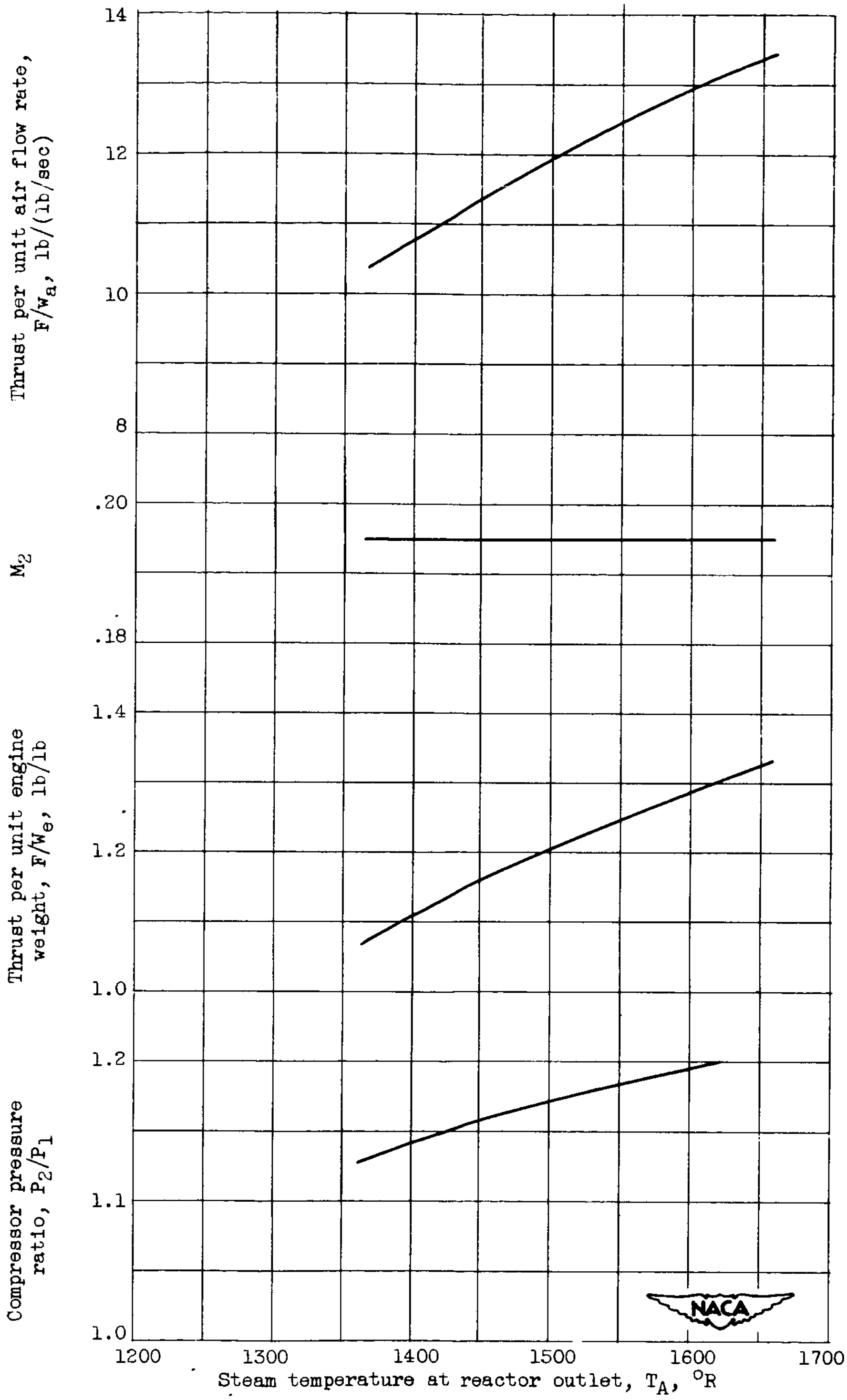

Figure 11. - Optimum values of P_2/P_1 and M_2 and corresponding values of F/W_e and F/w_a at various values of T_A. Flight Mach number, 1.5; altitude 50,000 feet; P_A, 5000 pounds per square inch; P_B, 2500 pounds per square inch.

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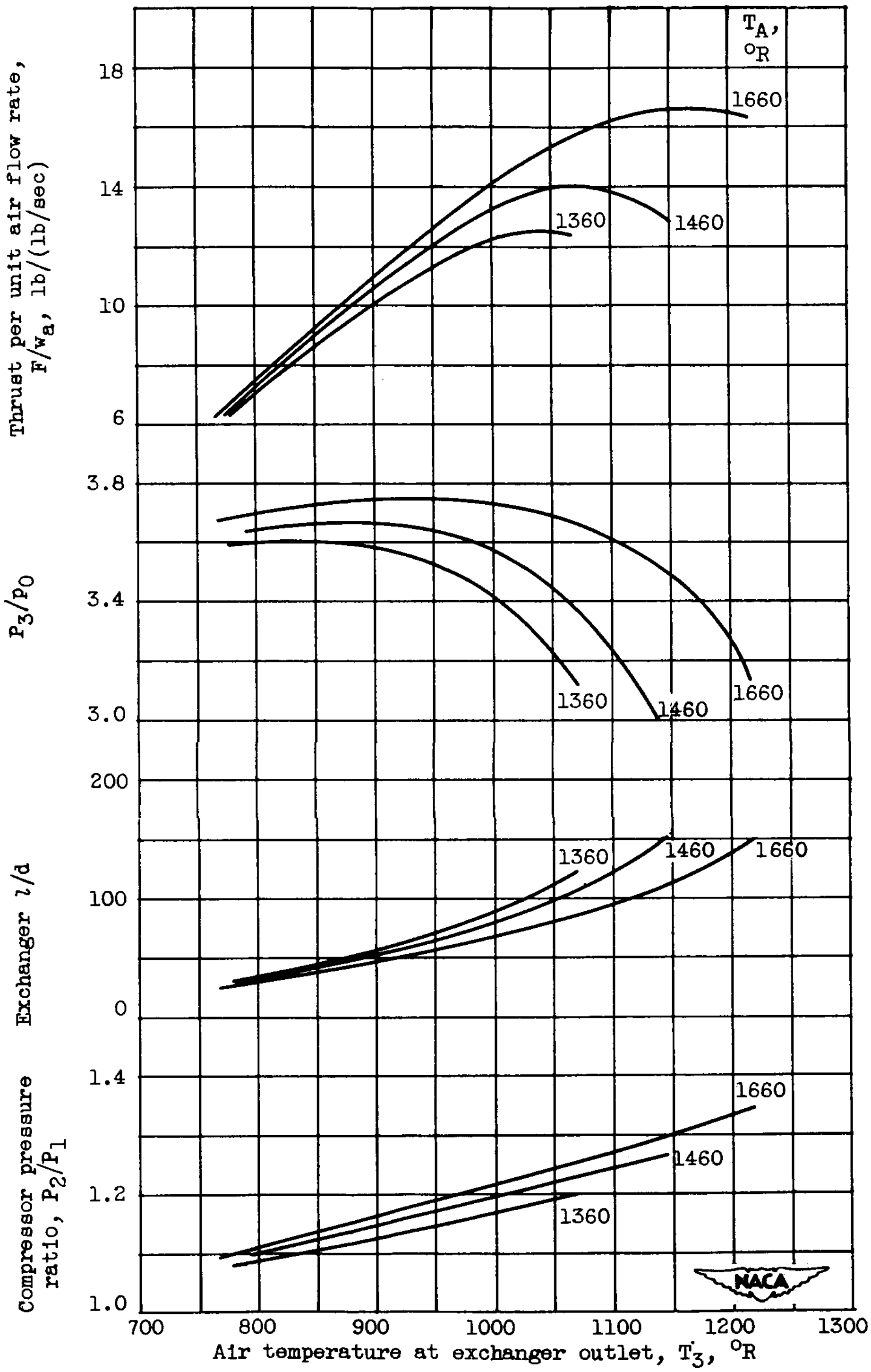

Figure 12. - Effect of T_A on engine component performance and over-all cycle performance. Flight Mach number, 1.5; altitude, 50,000 feet; P_A, 5000 pounds per square inch; P_B, 2500 pounds per square inch; M_2, 0.20.

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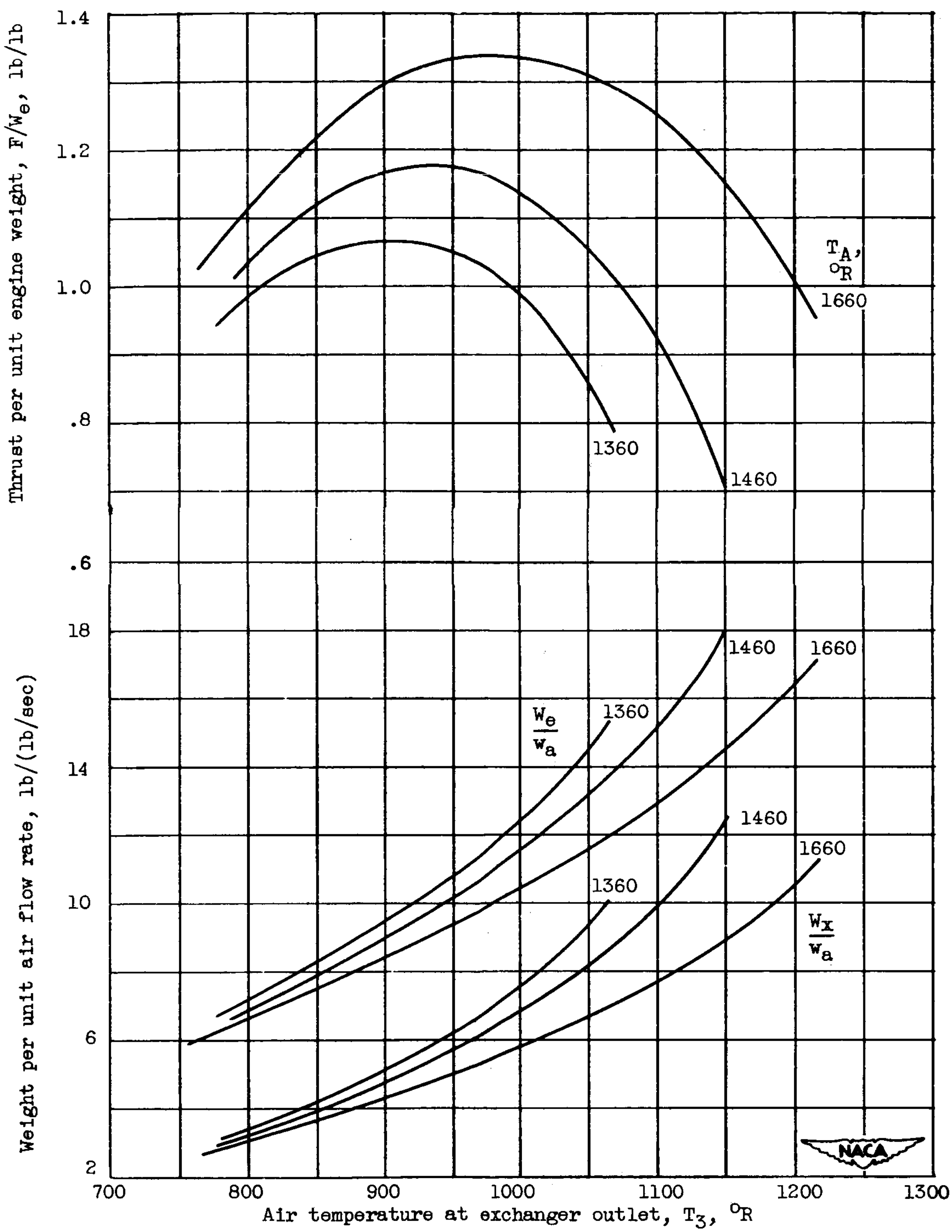
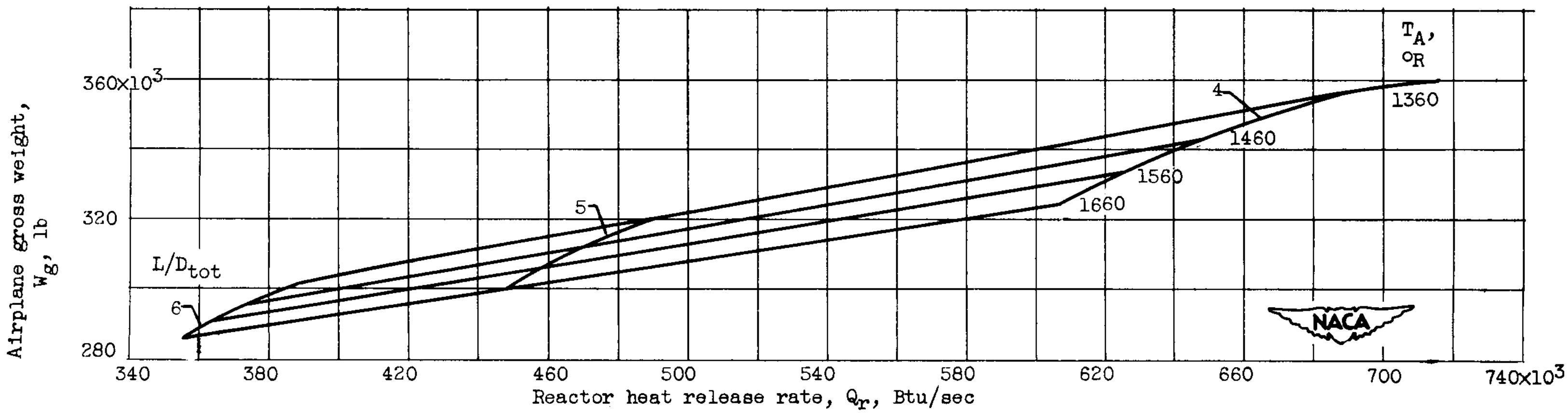


Figure 12. - Concluded. Effect of T_A on engine component performance and over-all cycle performance. Flight Mach number, 1.5; altitude, 50,000 feet; P_A, 5000 pounds per square inch; P_B, 2500 pounds per square inch; M_2, 0.20.



(a) Values of W_g against Q_r.

Figure 13. - Performance at optimum P_2/P_1 and M_2 for various values of L/D_{tot} and T_A. Flight Mach number, 1.5; altitude, 50,000 feet; P_A, 5000 pounds per square inch; P_B, 2500 pounds per square inch; W_s/W_g, 0.35; W_k, 150×10^3 pounds.

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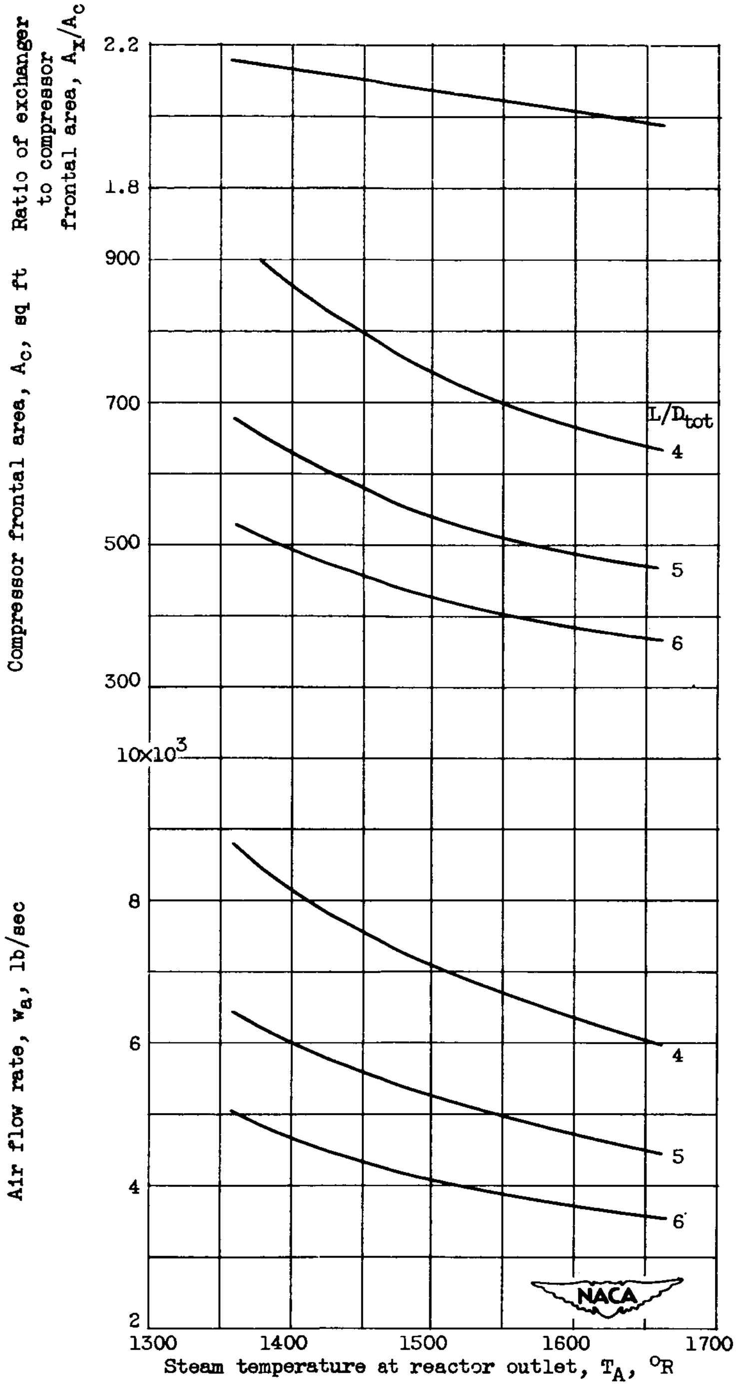

(b) Values of w_a, A_c, and A_x/A_c.

Figure 13. - Concluded. Performance at optimum P_2/P_1 and M_2 for various values of L/D_{tot} and T_A. Flight Mach number, 1.5; altitude, 50,000 feet; P_A, 5000 pounds per square inch; P_B, 2500 pounds per square inch; W_s/W_g, 0.35; W_k, 150×10^3 pounds.

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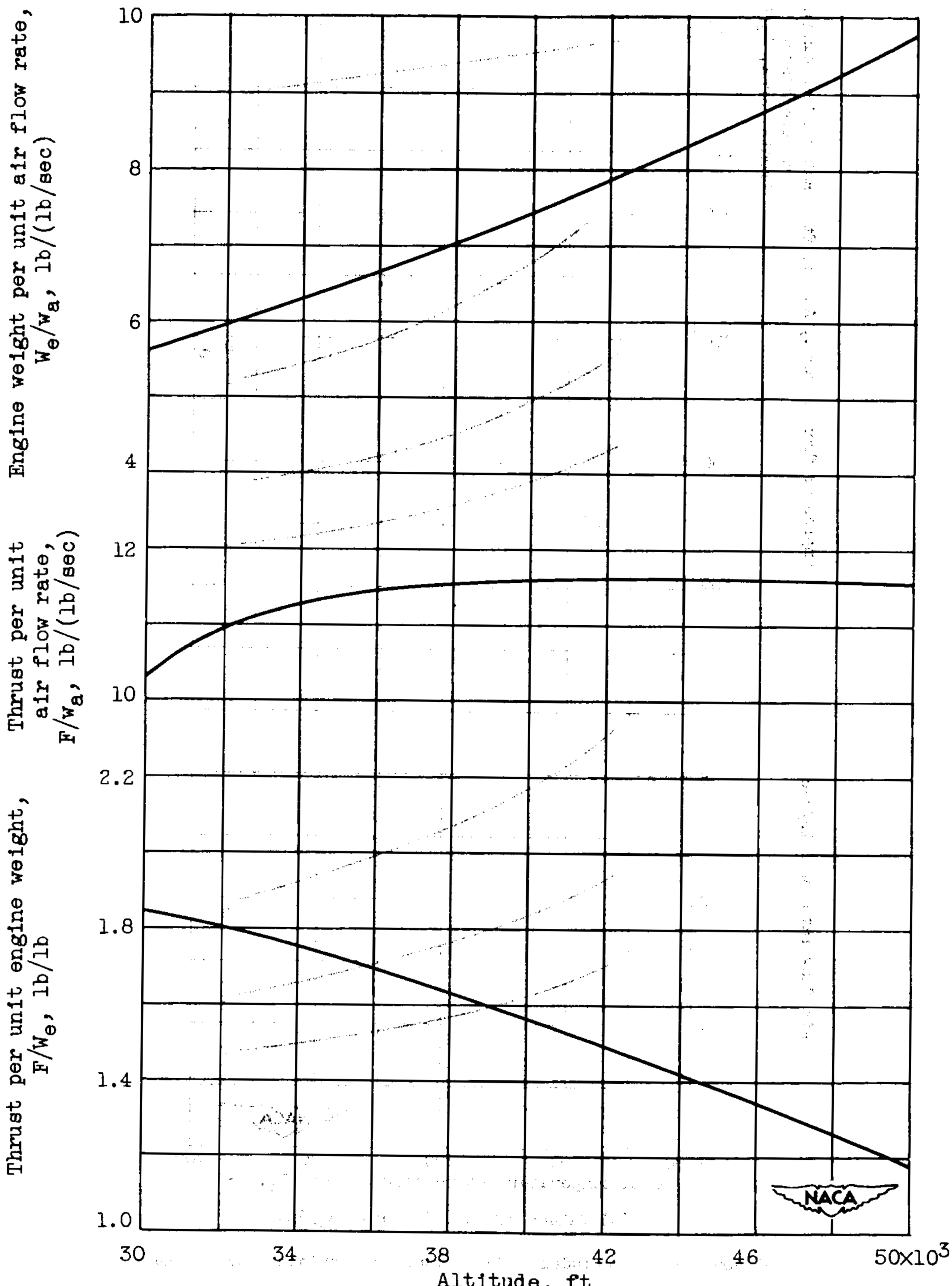

Figure 14. - Effect of altitude on the optimum values of F/W_e and corresponding values of F/w_a and W_e/w_a. Flight Mach number, 1.5; T_A, 1460° R; P_A, 5000 pounds per square inch; P_B, 2500 pounds per square inch.

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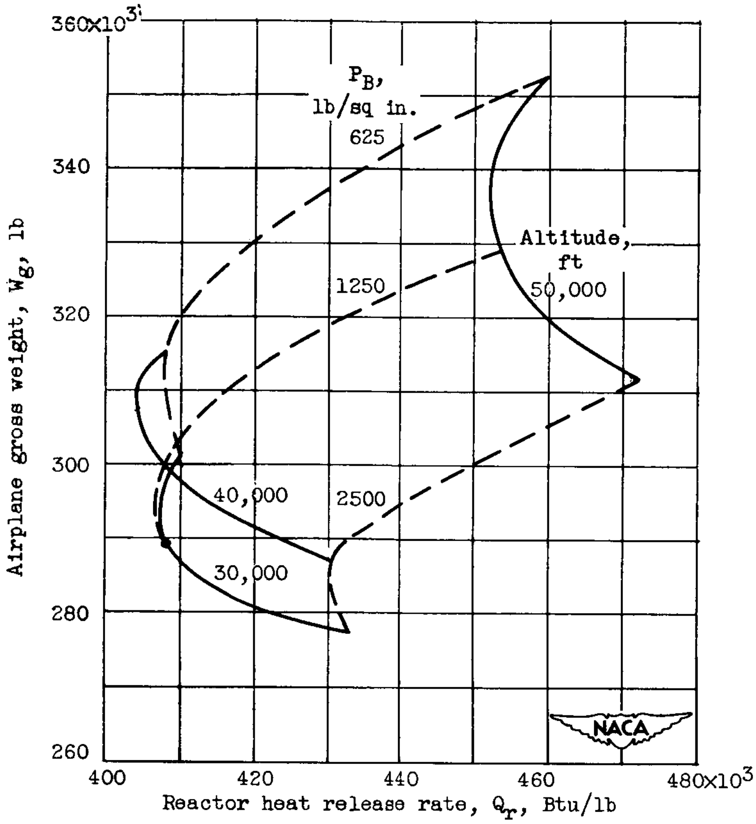
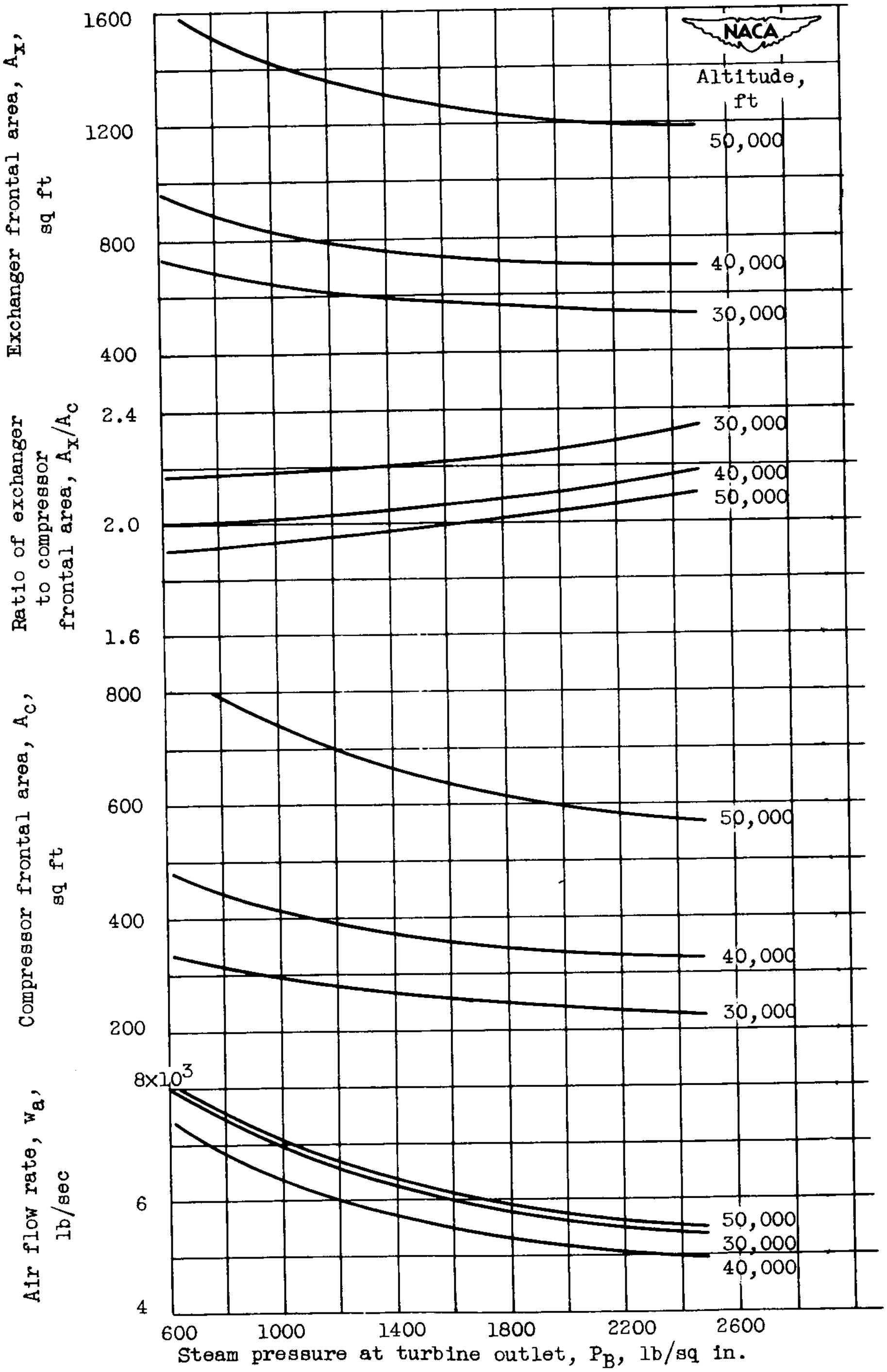


(a) W_g against Q_r.

Figure 15. - Performance at optimum values of P_2/P_1 and M_2 at various altitudes and values of P_B. Flight Mach number, 1.5; T_A, 1460° R; P_A, 5000 pounds per square inch; L/D_{tot}, 5; W_s/W_g, 0.35; W_k, 150,000 pounds.



(b) Values of w_a, A_c, A_x/A_c, and A_x.

Figure 15. - Concluded. Performance at optimum values of P_2/P_1 and M_2 at various altitudes and values of P_B. Flight Mach number, 1.5; T_A, 1460° R; P_A, 5000 pounds per square inch; L/D_{tot}, 5; W_s/W_g, 0.35; W_k, 150,000 pounds.

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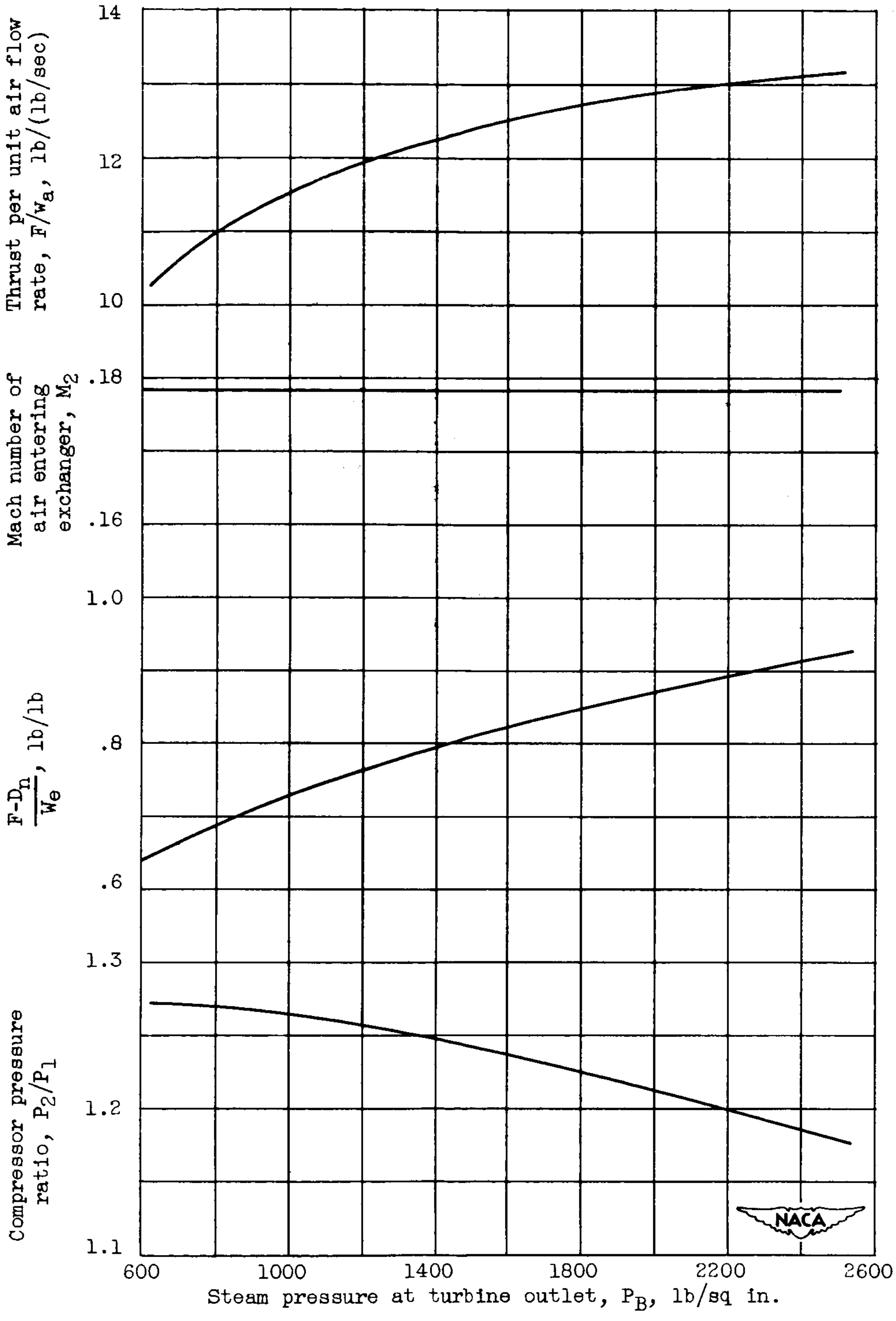
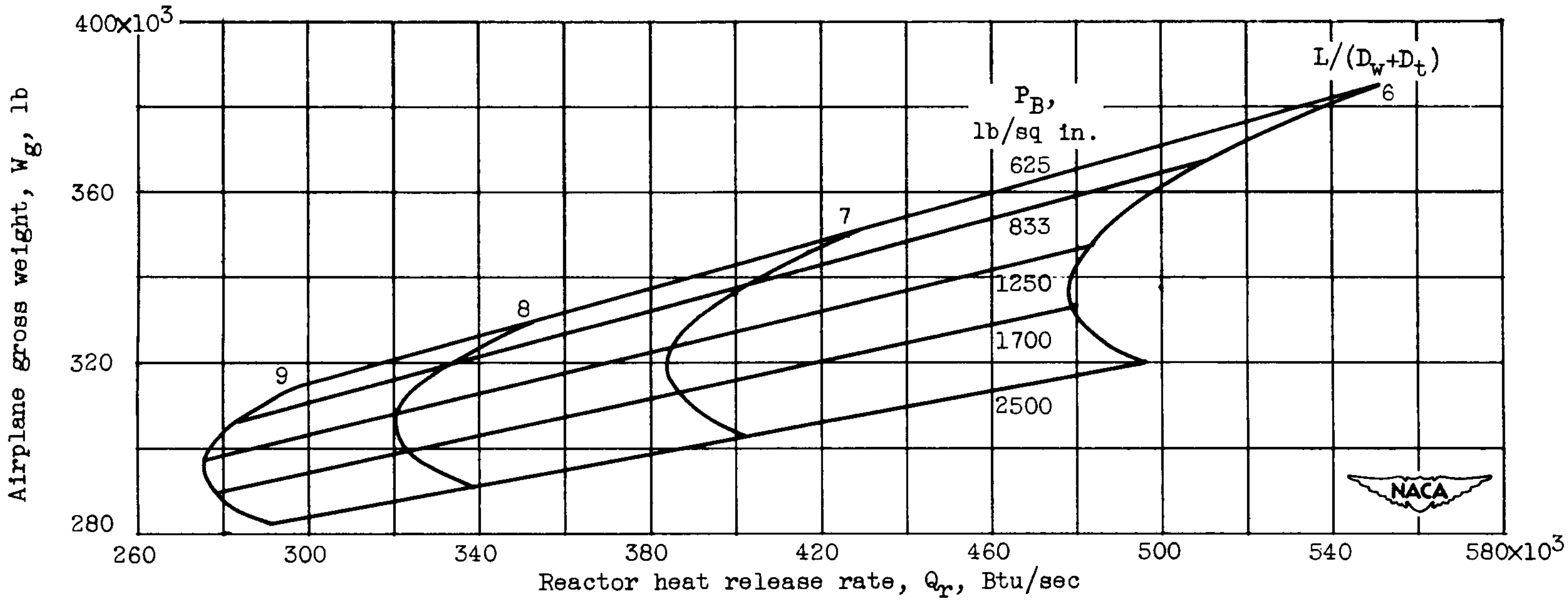


Figure 16. - Values of optimum $(F-D_n)/W_e$ and corresponding values of P_2/P_1, M_2, and F/w_a for various values of P_B. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; D_n/w_a, 2.69 pounds per pound per second.



(a) W_g against Q_r.

Figure 17. - Performance at conditions for optimum $(F-D_n)/W_e$ for various values of $L/(D_w+D_t)$ and P_B. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; D_n/w_a, 2.69 pounds per pound per second; W_s/W_g, 0.35; W_k, 150×10^3 pounds.

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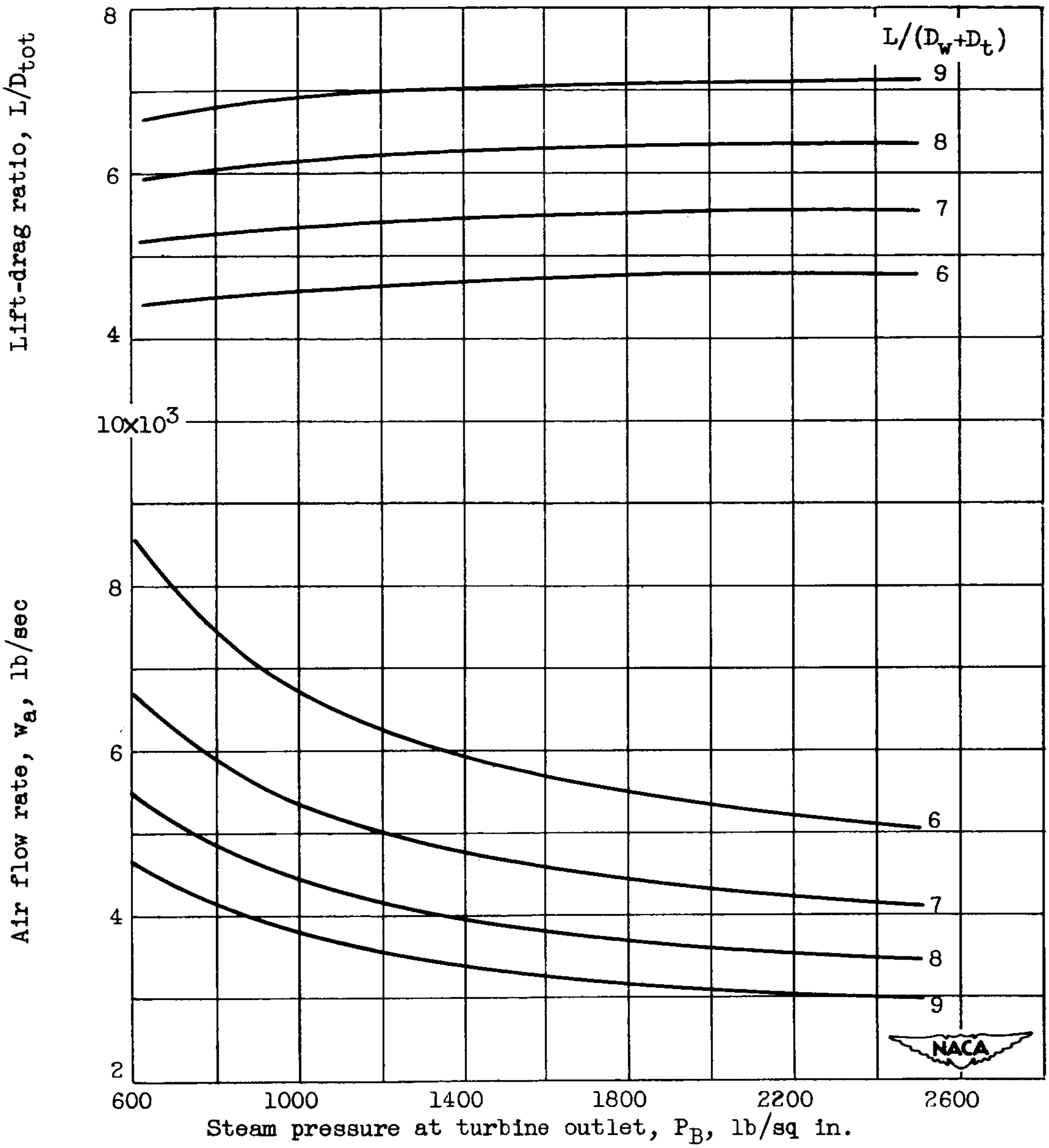

(b) Values of w_a and L/D_{tot}.

Figure 17. - Concluded. Performance at conditions for optimum $(F-D_n)/W_e$ for various values of $L/(D_w+D_t)$ and P_B. Flight Mach number, 1.5; altitude, 50,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; D_n/w_a, 2.69 pounds per pound per second; W_s/W_g, 0.35; W_k, 150×10^3 pounds.

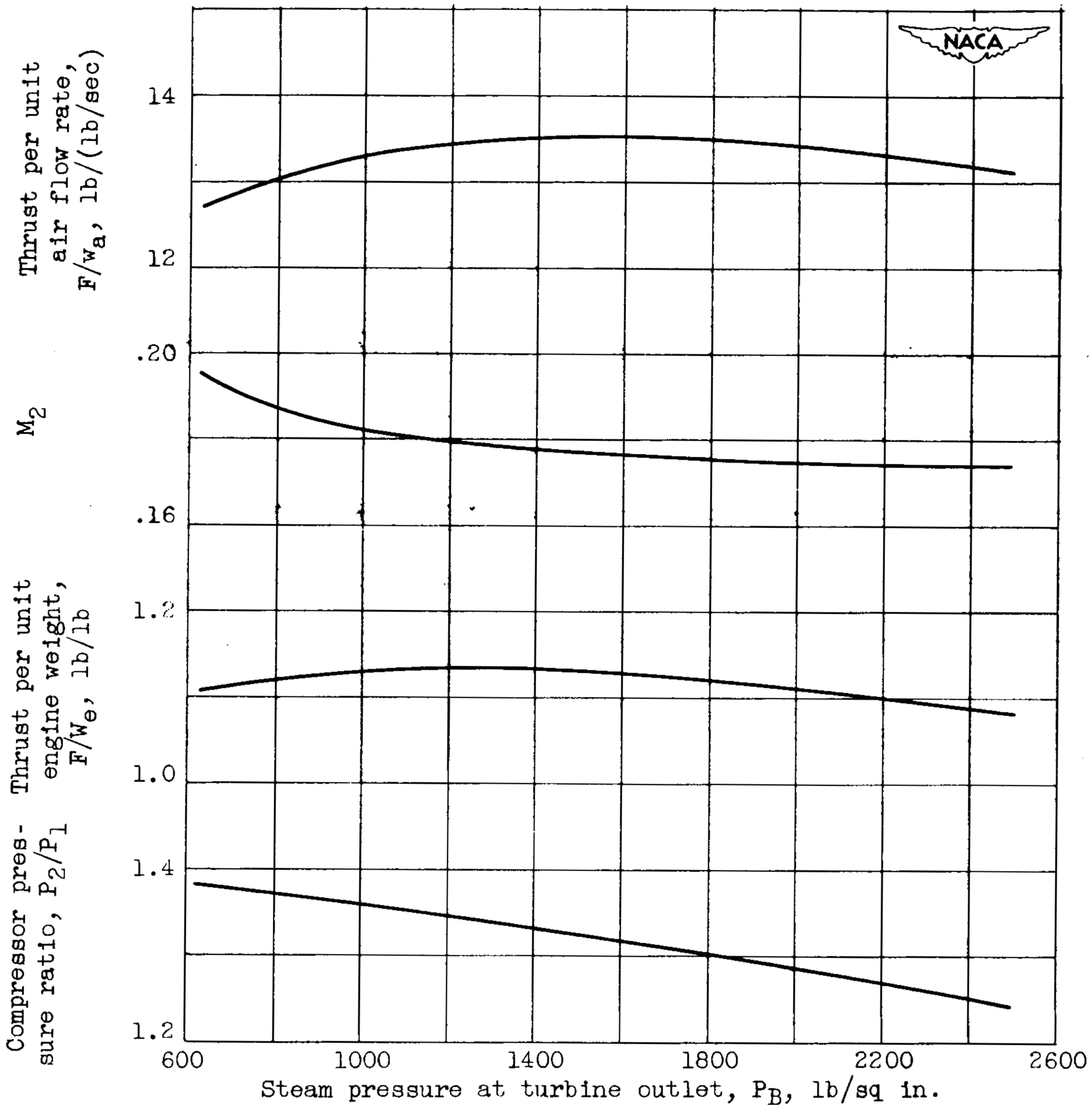

Figure 18. - Values of optimum F/W_e and corresponding values of P_2/P_1, M_2, and F/w_a. Flight Mach number, 0.9; altitude, 40,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch.

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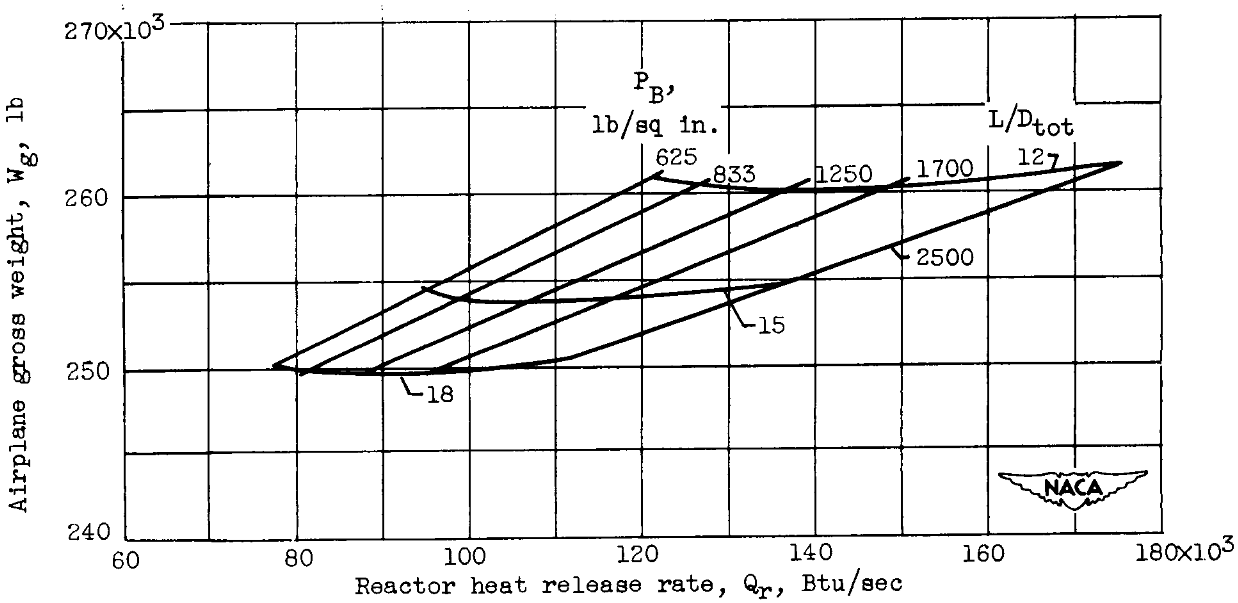
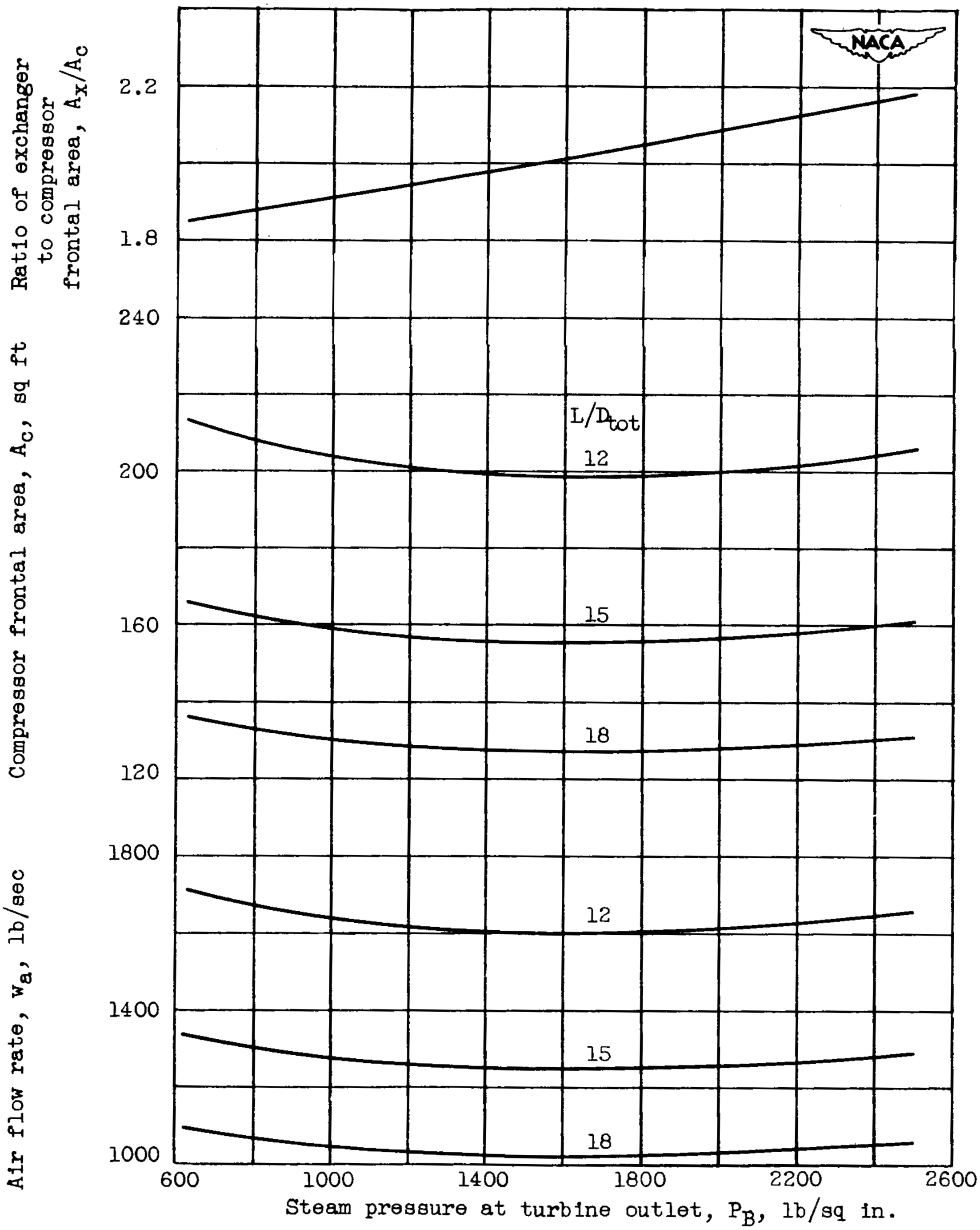


(a) W_g against Q_r.

Figure 19. - Performance at conditions for optimum F/W_e for various values of L/D_{tot} and P_B. Flight Mach number, 0.9; altitude, 40,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; W_s/W_g, 0.35; W_k, 150×10^3 pounds.



(b) Values of w_a, A_c, and A_x/A_c.

Figure 19. - Concluded. Performance at conditions for optimum F/W_e for various values of L/D_{tot} and P_B. Flight Mach number, 0.9; altitude, 40,000 feet; T_A, 1460° R; P_A, 5000 pounds per square inch; W_s/W_g, 0.35; W_k, 150×10^3 pounds.

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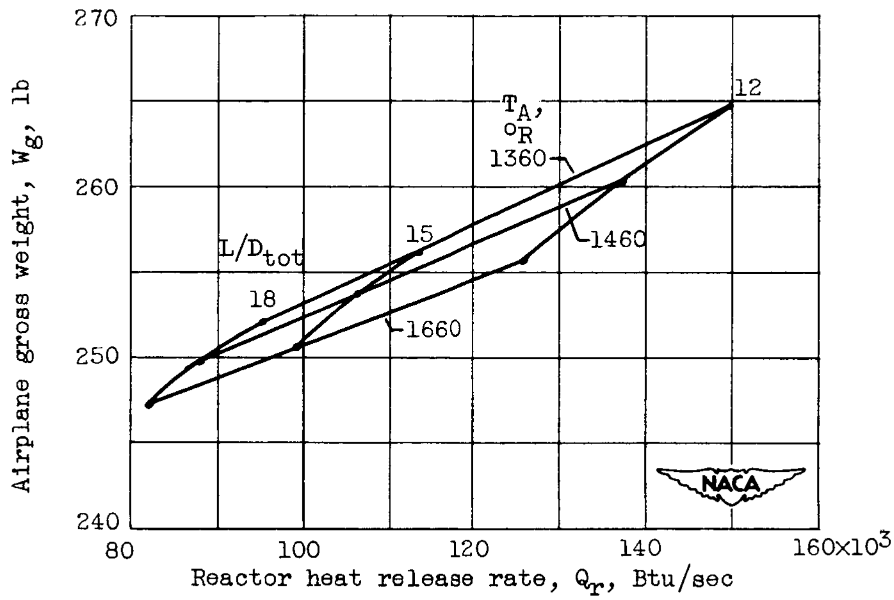

(a) W_g against Q_r.

Figure 20. - Performance at conditions for optimum F/W_e for various values of L/D_{tot} and T_A. Flight Mach number, 0.9; altitude, 40,000 feet; P_A, 5000 pounds per square inch; W_s/W_g, 0.35; W_k, 150×10^3 pounds.

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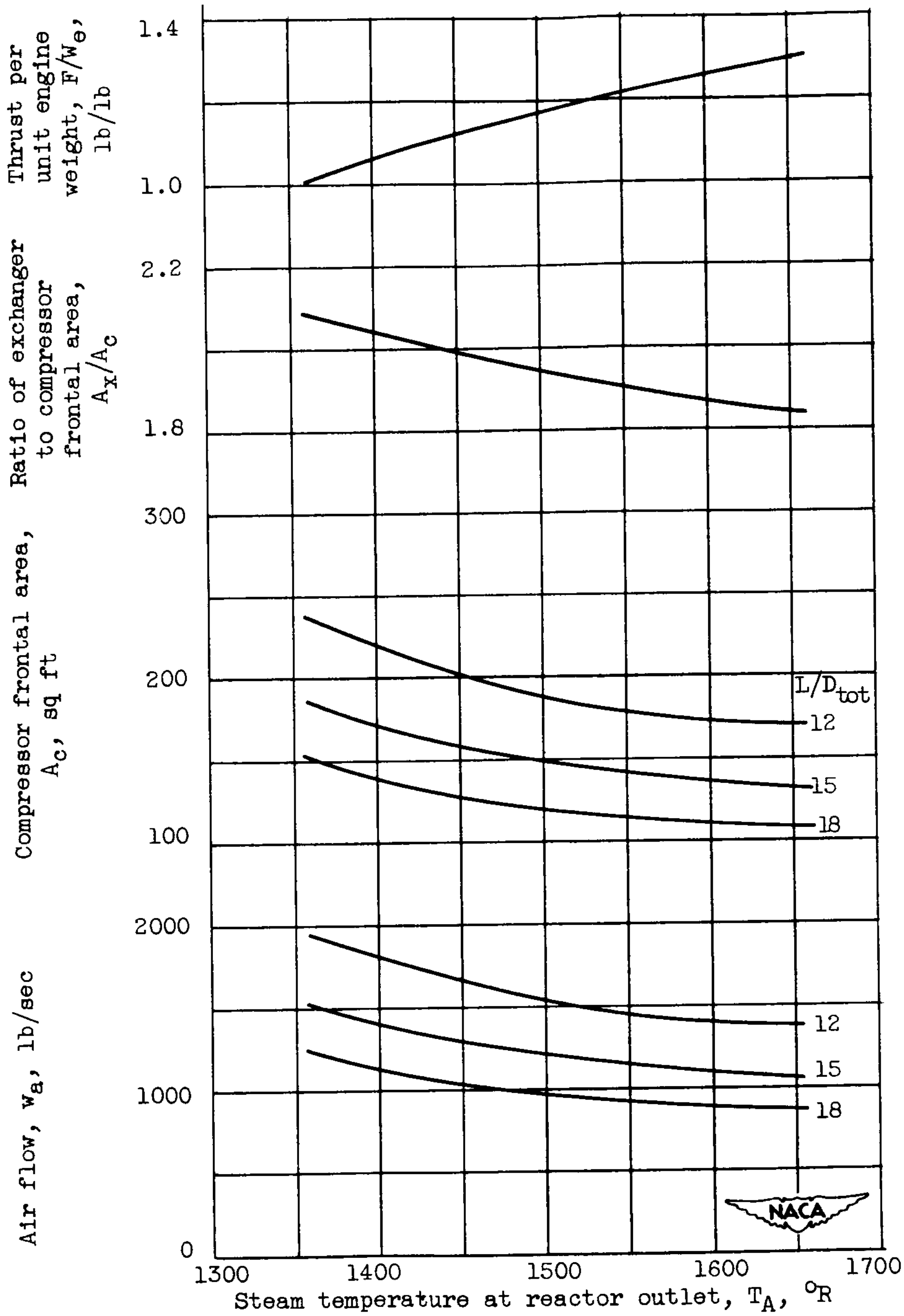

(b) Values of w_a, A_c, A_x/A_c, and F/W_e.

Figure 20. - Concluded. Performance at conditions for optimum F/W_e for various values of T_A and L/D_{tot}. Flight Mach number, 0.9; altitude, 40,000 feet; P_A, 5000 pounds per square inch; P_B, 1250 pounds per square inch; W_s/W_g, 0.35; W_k, 150×10^3 pounds.

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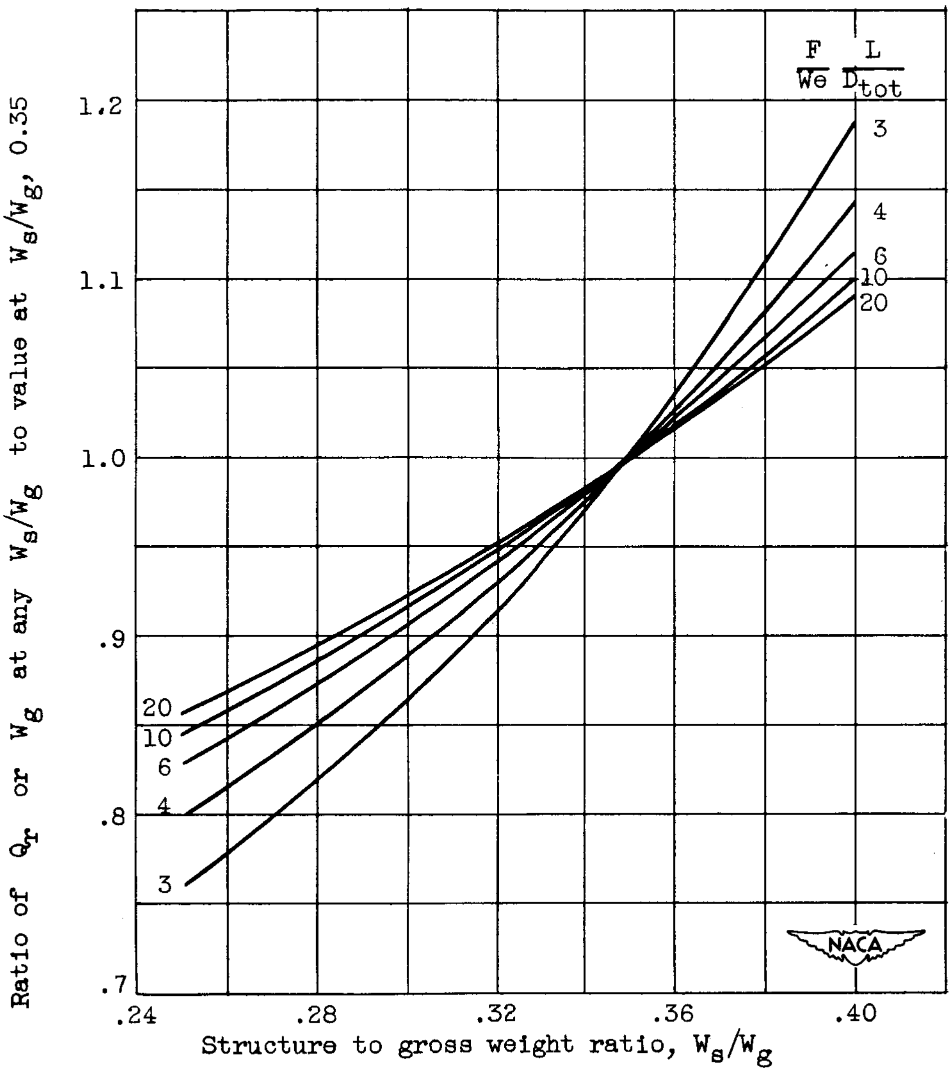

Figure 21. - Effect of W_s/W_g on values of W_g and Q_r.